

**POTENTIAL OF COMBUSTION OF POULTRY LITTER FOR SPACE
HEATING IN POULTRY PRODUCTION**

By

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DECLARATION

The work contained in this dissertation was compiled by the author at the University of Zambia. To the best of my knowledge it contains no material previously published by another person or material which has been accepted by any other degree of any other university except where due acknowledgement and reference has been made in the text.

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CERTIFICATE OF APPROVAL

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ABSTRACT

Confined poultry production, which is expected to double by 2050, produces a lot of manure. For successful and sustainable poultry production, manure management is prompted and should be prioritized. Poultry litter can serve as an energy feedstock for space heating and electricity generation. Currently, the heating systems in use depend on electricity, charcoal or diesel which are very expensive leading to high energy costs in poultry production. The purpose of this study was therefore to investigate the potential of combustion of poultry litter briquettes for space heating in poultry production.

The briquettes were made with a mincer which had a nozzle of dimensions, Length=11 cm and Diameter= 25 mm producing briquettes of a diameter of 25 mm and a length of 10 cm. The briquettes were made from poultry litter of chickens at the ages of 4, 5 and 6 weeks, and were either sun or solar dried. Subsequent to drying, the moisture content variation with time was fitted into thin layer drying equations to determine the drying behavior of Poultry Litter Briquettes. A kilogram of the briquettes was then directly combusted in a brazier with 32 holes, of a diameter of 1cm, on its sides comprising of dimensions; Diameter=8 cm and Height=65 cm and heat distribution was measured at distances of 30 cm, 60 cm and 90 cm from the brazier. Charcoal was used as control. The calorific value of the briquettes at different week ages was determined.

Maximum average temperatures recorded on the surface of the brazier for week 4, 5, 6 were 471°C, 491°C, 493°C respectively; whereas for charcoal it was 555°C. Complete combustion for poultry litter briquettes took an average of 120 minutes while charcoal took an average of 180 minutes. For poultry litter briquettes at week 4 under open sun drying, the calorific value was found to be 15.65 MJ/kg whereas for those at week 6 under solar tunnel drying was 14.57 MJ/kg which were almost similar. Recommendations were that briquettes which had been compacted more and of larger sizes be experimented on to check the efficiency of the briquettes. Alternatively, more briquettes could be added as the combustion takes place so that the level of heating can be maintained.

KEYWORDS: Poultry Litter, Poultry Litter Briquettes, Thin Layer Drying, Direct Combustion, Calorific Value

DEDICATION

This dissertation is dedicated to the well-being of the earth, to its sustainability to nurture younger upcoming generations in good health and productivity. The world can be made a better place by the present generation for the future generation. LIVE A LEGACY TO LEAVE A LEGACY.

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LIST OF ABBREVIATIONS

PL	Poultry Litter
PLB	Poultry Litter Briquettes
T _{CH}	Chimney Temperature
T _{DU}	Drying Unit Temperature
T _{CU}	Collector Unit Temperature
T _{AM}	Ambient Temperature
H _D	Heat Distribution
DC	Direct Combustion
OSD	Open Sun Drying
STD	Solar Tunnel Dryer
MC	Moisture Content
CV	Calorific Value
UNZA	University of Zambia
B _{ST}	Brazier Surface Temperature
LPG	Liquid Petroleum Gas
ZABS	Zambia Bureau of Standards
ANOVA	Analysis of Variance
SPSS	Statistical Package for Social Sciences
LSD	Least Significant Difference
METEGA	Mobility to Enhance Training of Engineering Graduates in Africa

NOMENCLATURE

MC_{db}	Moisture Content in dry basis
MC_{wb}	Moisture Content in wet basis
MC_t	Moisture Content at any time
MC_0	Initial Moisture Content
W_i	Initial Weight
W_f	Final weight
MR_t	Moisture Ratio at any time
R^2	Correlation Coefficient
χ^2	Chi-squared
RMSE	Root Mean Square Error
MR_{pre}	Predicted Moisture Ratio
MR_{exp}	Experimental Moisture Ratio
M_{ash}	Mass of ash
$M_{briquette}$	Mass of briquettes
CO_2	Carbon Dioxide
GHG	Green House Gases
CO	Carbon monoxide
NO_x	Nitrogen Oxides
NH_3	Ammonia
Cd	Cadmium
Hg	Mercury
HCL	Hydrochloric acid
TI	Titanium
SO_2	Sulphur Dioxide

CHAPTER 1 INTRODUCTION

Zambia is a landlocked country in Southern Africa and located between latitudes 8° and 18° south and longitudes 22° and 34° east and occupies an area of 752,612 square kilometers. Also, the economy of Zambia is based on Mining, Agriculture, Construction, Transport and Communication sectors (Central Statistical Office, 2012). It is surrounded by neighbours The Democratic Republic of Congo, Tanzania, Malawi, Mozambique, Zimbabwe, Botswana, Namibia, and Angola. Zambia's population is reported to have an exponential growth since gaining its independence, rising from 3.5 million in 1964 to 16 million in 2016. Moreover, Zambia's population growth is among the most rapid in the world, averaging 3% per year (Ngoma *et al.*, 2018). The staple food in Zambia is maize which is also the country's dominant agricultural activity. Furthermore 65% of the production of maize is found among smallholder farmers which accounts to 25% of the marketed maize (Saasa, 2003).

The poultry industry in Zambia contributes 4.8% to the agricultural Gross Domestic Product and 48% to the livestock sector. Additionally, income is generated through the sale of eggs, broiler meat and culled hens (Bronkhorst and Chongo, 2015). Poultry is considered as a domesticated fowl which includes chicken, turkey, guinea fowl, pigeons, ostriches and swimming birds such as duck and geese (Adeyemo and Onikoyi, 2012).

In Zambia bird production includes both village chicken and conventional broiler chickens in where village chicken comes from the indigenous domesticated chicken and often scavenges for feed (Andersson, 2014). More than 93% of the population in the rural areas own indigenous Zambian chickens (Andrew, 2011). Their maintenance is cheap. Broiler production is increasing although it is not common in rural areas because of associations with high risks as compared to village chicken due to expensive investments but profitable when slaughtered. In addition, Zambia has both small-scale broiler farmers, keeping few birds for their consumption, and large-scale industrialized broiler farmers, who keep several thousands of chickens, and all sizes of farms in between (Andersson, 2014).

Each year approximately 56 billion land animals are raised for slaughter worldwide for human consumption and by 2050 livestock inventories are expected to double,

mostly in developing countries. Also, most of these animals are confined and produce a lot of manure which is perceived as a waste but must be handled properly in favour of the environment (Lynch *et al.*, 2013). The litter or manure produced is normally used as an organic fertilizer since it is rich in nutrients and this practice was traditionally implemented for soil amendment. However, mismanagement of this practice can bring the risk of surface and groundwater contamination when manure or litter is over applied to soil (Kelleher *et al.*, 2002). Human health, the environment and the quality of life for people living around poultry production operations make waste management a critical consideration for the long-term growth and sustainability of poultry production. In addition, ammonia emissions disturb air quality and this is classified as the major pollutant to the environment when it comes to poultry production (Williams, 2008).

As a mitigation measure, green and sustainable solutions have to be made so that health and environmental concerns are diminished with regard to increasing poultry litter quantities. Similarly, poultry litter contains relatively high energy content and fixed carbon, therefore producing both bioenergy and sustainable biochar from it provides an alternative for waste management (Huang *et al.*, 2015). Waste materials removed from poultry houses, can serve as an energy feedstock for heating and electricity generation for poultry production (Jensen *et al.*, 2009).

1.1 Statement of the Problem

Poultry production results in hatchery wastes, manure, litter, and on-farm mortalities. Since the poultry business is growing vigorously in Zambia, leading to more poultry waste production, the disposal of it has become one of the problems encountered after the poultry houses are cleared. This waste is often tied up in bags and left near the production site and this gives rise to potential environmental and human health concerns as the sources of elements, compounds, vectors for insects and pathogenic microorganisms.

In terms of energy requirements, large quantities of fuel are consumed in the poultry industry for their heating systems used to maintain the required temperatures. Currently, the heating systems in use depend on either electricity, charcoal or diesel which are very expensive leading to high energy costs. Energy costs constitute a significant portion, often over half, of cash expenses for poultry producers. Rapid

increases in costs highlight the need for investigation of poultry house energy requirements, alternative energy, and conservation practices.

1.2 Significance of the Study

Application of poultry litter to the ploughed land as a way of increasing crop productivity and yield has been an adopted practice from the previous years. This serves as a waste management strategy, however if not applied judiciously, the poultry litter can contaminate groundwater since the water table in Zambia is relatively high. Apart from using poultry litter as a fertilizer, there are cases where the litter is cleared and filled into large bags and is left on an open area which poses as a health hazard to humans living near the poultry site as well as the workers due to its bad odour. This kind of disposal can also be harmful to the livestock inventory since the litter becomes a source of harmful bacteria, flies and diseases which is not good for production.

With the upward adjustments of electricity tariffs here in Zambia as well as the fuel prices fluctuating, heating the poultry houses is a challenge since the energy costs incurred are high. This challenge can be met by recovering energy from the poultry litter thus minimizing costs. There is therefore a need to determine the heat potential of poultry litter to produce heat for poultry production because this can help prevent the potential of groundwater contamination, reduce odour problems (methane emissions) and killing pathogenic microorganisms leading to a healthy environment for both humans and livestock. Moreover, this would benefit poultry producers greatly because of the cheap way of accomplishing the required temperatures of the poultry houses hence energy costs should be less.

1.3 Objectives of the Study

1.3.1 Overall Objective

- To investigate the potential of poultry litter to provide heat for use in poultry production

1.3.2 Specific Objectives

1. To produce Poultry Litter Briquettes and establish thin layer mathematical models that predict their drying
2. To determine the heat production from the brazier combusting Poultry Litter Briquettes produced from poultry litter of 3 different week ages
3. To determine heat distribution during direct combustion of Poultry Litter Briquettes at 3 different week ages
4. To determine the calorific value of Poultry Litter Briquettes

1.4 Research Questions to be Answered

1. How are mathematical models of poultry litter briquettes going to be established?
2. How is heat production from poultry litter briquettes going to be carried out?
3. How is the heat distribution from combustion of poultry litter going to be determined?
4. How the calorific value of poultry litter briquettes is going to be determined?

1.5 Scope of the Study

This study intended to provide a solution to the problem of high energy costs during space heating of poultry houses when temperatures are low. A mincer was used to make poultry litter briquettes which were dried using a Solar Tunnel Dryer and Open Sun Drying at the Department of Agricultural Engineering at the University of Zambia. The Solar Tunnel Dryer was used for thin layer drying of poultry litter briquettes at the Department of Agricultural Engineering Field Station.

The performance of the dryer was compared with open sun drying. Thin layer mathematical models were developed to predict the drying of poultry litter briquettes of length 10cm and diameter of 25mm under the Solar Tunnel Dryer and Open Sun Drying. The dried briquettes were then directly combusted in a brazier to measure the heat produced as well as its distribution at distances of 30cm, 60cm and 90cm from the brazier. The calorific value of the briquettes was also determined at Zambia Bureau of Standards.

1.6 Closing Remarks

This chapter highlighted the problems associated with poultry production in Zambia, in relation to heat energy requirements, and how this study was aimed at providing a solution to these challenges. The chapter also explained why poultry litter was chosen for this study. Finally the objectives, significance and scope of this study were covered. The next chapter reports in detail the necessary literature reviewed for this study.

CHAPTER 2 LITERATURE REVIEW

This chapter presents literature in line with the topic of this research work. Inclusive are research work on poultry litter, heating poultry houses and what is used to heat the poultry houses.

2.1 Poultry And its Environmental Requirements

The environment serves as a vital input to the livestock sector therefore, the livestock-environment interrelationship should be understood for their production and management. Physiological processes and behavioral changes of poultry are directly affected by climate. Temperature is one of the most significant environmental factors determining performance in poultry birds. Narrow temperature ranges can be tolerated by poultry birds to sustain the peak of their production. Any deviation from the tolerated temperature range will cause their thermoregulatory mechanisms for survival leading to negative consequences on their performance (Jini *et al.*, 2015).

Environmentally controlled poultry houses are used to raise livestock in poultry farms in order to maintain the temperatures required for the breeding of the chicks (Harmra, 2010). The required temperature of any broiler house ranges from 22°C to 32°C depending on the bird's age. Feed intake will be increased by birds through the use of feed energy to keep their bodies warm if they are kept at lower temperatures thus production costs are increased while meat yield is decreased. If kept at high temperatures, they reduce their feed intake to limit heat production also resulting in lower meat yield. An efficient heating system is therefore a necessity for any broiler house to maintain the required temperatures (Zanaty, 2015).

In line with this, Nabangi, (2015) also stated that the digestive and immune systems of chicks become impaired when exposed to low temperatures. Additionally, death can be caused by low temperatures due to opportunistic infection and overcrowding. When low temperatures are experienced, young chicks have a tendency of crowding together, this may as a disadvantage result in smaller chicks getting suffocated by the larger chicks. Provision of adequate heat is essential during brooding but a chick can go without food for the first three days of its life but cannot survive without adequate heat.

Lynch *et al.*, (2013) reported that it is vital to implement temperature control during the initial stages of broiler production in northern and temperate climates, which involves using an external heat supply for the first four weeks of the production cycle. It was further stated that heat requirement is reduced in the later stages of the cycle. Moreover, poultry houses are heated using fossil fuels and due to increasing energy costs, ventilation of sheds has been reduced by some farmers in an attempt to reduce costs. This is said to be hazardous to bird health as it can increase the moisture content of the litter, leading to hock burn and dermatitis and can also lead to the buildup of harmful emissions such as ammonia and carbon monoxide thus increasing bird mortality. Nevertheless harmful gases must be exhausted from the poultry houses while suitable temperatures are maintained especially during winter (Guerra *et al.*, 2016).

The amount of fuel used for heating a poultry house depends on factors like climatic conditions and the amount of heat produced by the chicken within the space to be heated. The lowest air temperatures reached during winter and the annual mean air temperature are defined by the location of the house. This consequently determines the amount of space heating needed inside the house. Also, the amount of heat leakage to the outer atmosphere is indicated by the extent to which the poultry house is insulated. The degree to which chickens produce latent and sensible heat is based on their weight, age and brooding temperature. Thus, the number of birds housed per volume and their weight affects the amount of heat needed to maintain a certain set temperature at this volume.

In a research by Fanatico (2007), it was pointed out that under any climate, insulation under the roof to modulate temperatures is important. Wall insulation is as well helpful. It was further stated that when it is hot, heat is prevented from entering the house by insulation and when it is cold, the insulation keeps heat from leaving the building. There is therefore a dire necessity for insulation when the difference in temperatures between the outside and inside environment is of a greater margin. Provision of assistance to temperature regulation inside the house is through proper ventilation.

The heating or cooling and air quality needs of poultry in a poultry house as well as supply of fresh air is achieved through ventilation. According to Almuhanha, (2016) the major purpose of a ventilation system is to sustain the wellbeing of confined animals and enhances production through the provision of an aerial environment. Similarly, hyperthermia is prevented by maximum ventilation rate, while the minimum ventilation rate provides an acceptable thermal and aerial environment for animal performance.

During winter, the air surrounding the animal and the objects in the poultry house are mostly cold. Hence this presents a way in which heat can be lost from the confined animals. In relation to the study by Manjunatha, (2017), radiation provides a means of heat loss from the body of the animal since the temperature in the house will be lower than that of the animal. The heat loss from the animal to the surrounding environment stops when their temperatures are equal. Furthermore, convection is also another way in which poultry lose their body temperature. This is through surrounding objects especially air. When the surface of the bird is exposed to cold air, the air gets warmed up then expands. As a result, the air will rise carrying heat away from the bird thus leading to heat loss.

Birds have the ability to acclimatize to the environment by maintaining their body temperatures to the ones required by their bodies which is a good mechanism they possess but cannot be relied on since it leads to poor production in terms of performance and also unnecessary costs. Yu *et al.*, (2017) states that efficient raising of birds takes into account their specific requirements during different growing stages. Additionally, to obtain good performance from the birds in a given timeframe, the poultry house temperature has to be considered. Thus, in winter energy must be provided to keep the poultry house temperatures to those required by the birds since outdoor temperatures change.

2.2 Poultry Litter

Due to the rapid growth of the poultry sector in Zambia, this has led to more generation of poultry manure and litter which now causes disposal conflicts. There is such great demand of poultry meat because of its provision of proteins as well as its low cholesterol levels. Currently, the produced litter is mostly used for land application in agricultural lands. However, the continual use of the litter for soil amendment may

pose risks of contamination of underground water since Zambia has a relatively high water table. The application also leads to unpleasant odours which attract flies and different microorganisms thus posing a health hazard to humans surrounding the area.

Shakya and Agarwal (2017), states that it has been a long time practice to use poultry litter directly with or as compost in soil though this results in concerns regarding mineral runoff and other environmental threats. Additionally, when more poultry litter is applied than the targeted crop requires, this may lead to environmental contamination. Moreover, threats to the environment can also occur when the addition of poultry litter is implemented where there are poor management conditions which causes nutrient loss from environmental factors such as soil erosion or surface runoff during rainfall. Goyal and Phutela (2018), also highlighted that applying poultry litter excessively in soils leads to enriching of water nutrients which results in eutrophication of water bodies, the spread of pathogens as well as producing phytotoxic substances. It was further reported that nitrate (NO_3) contamination of groundwater can be experienced when poultry litter is over applied in arable lands which can also cause calamities such as methemoglobinemia (blue baby syndrome), cancer, and respiratory illness in humans and fetal abortions in livestock.

Confined animal production is the major source of manure by-products in many countries. Bird excreta combined with bedding material is defined as poultry litter (Butcher and Miles, 2015). The litter management, and feed intake and its digestibility determine the quantity of poultry litter produced in a poultry house. Poultry litter comprises mainly the bedding material, feathers, manure and the spilt feed. Bedding material constitutes of various objects such as wood shavings, cereal straw, husk and paper clippings. The litter contains plant nutrients, such as nitrogen, phosphorus and potassium, trace elements, such as Copper, Zinc and Arsenic. Health and feed efficiency can be improved through the usage of some of the trace elements as supplements as well as adding them to poultry feed as important nutrients (Bolan *et al.*, 2017). Also, observations have been made that on some of the poultry farms in Zambia poultry litter is stored in large bags awaiting purchase by people involved in arable farming.

A study by Kheiralipour *et al.*, (2017) reports that litter storing results in methane production. This is a gas with a pungent odour and is not good to health of people surrounding the area of production even to livestock being reared.

Ammonium assumes the form of nitrogen available in poultry litter. During combustion, ammonium is converted to ammonia by rapid volatilization (Dalólio *et al.*, 2017). Ammonia is the major noxious gas associated with poultry operations. Formation of ammonia is through rapid conversion of uric acid found in bird feces in the presence of microbes. When poultry houses are concentrated with ammonia, the feed intake of birds will be reduced thus hindering the growth rate (Xin *et al.*, 2011). This negatively affects production and leads to unnecessary costs. In addition, when combusted the ammonia formed converts NO_x to Nitrogen at elevated temperatures of around 800 °C. Differences were pinpointed regarding the use of poultry litter and its atmospheric emissions of nitrogen.

The emission was found to be 25 mg/kg when using poultry litter as fertilizer while in combustion or fluidized bed gasification it was 0.0017 mg/kg of litter. In regard to this, when using litter as fuel rather than as fertilizer, environmental pollution can be reduced (Dalólio *et al.*, 2017). Results regarding atmospheric of burning poultry litter and coal are presented in Table 2.1.

Table 2.1 Atmospheric emissions from the combustion of poultry litter and coal

Elements	Units	Poultry Litter	Coal
CO ₂	Kg	0.00	626.00
CO	Kg	0.05	0.15
NO _x	Kg	0.22	1.10
NH ₃	G	17.00	27.00
SO ₂	G	20.00	830.00
HCL	G	4.00	8.00
Hg	Mg	< 4.00 ^a	12.00
Cd + Tl (radioactive)	Mg	< 9.00 ^a	0.90
Heavy metals	Mg	< 65.00 ^a	262.00
Dioxins and Furans	Ng	< 44.00 ^a	53.00

^a Below the detection limits, overestimated value. Within the current standards of the European Union

source: (Dalólio et al., 2017)

A research by Hunolt, (2015) reports that the disposal of poultry manure to land is hazardous since it increases fecal contamination in food and waterways. It was further stated that the most common fecal bacterial indicator is *Escherichia coli* which is a gram-negative, rod-shaped, facultative anaerobe that causes several diseases in poultry and is subsequently harmful to human health. In addition, even when birds have been removed from the poultry house, this bacterium is said to remain and knowledge has been provided that colonies are found after 120 days of bird removal from the poultry house and after 2 months in soils. To mitigate this issue is if the poultry litter is treated which might be expensive thus this study focuses on using the poultry litter as a source of heat. This alternative will assist with preventive measures of the accumulation of *Escherichia Coli* in soils since poultry manure is continually being disposed off in agricultural lands here in Zambia.

To prevent harmful causes of poultry litter to the environment as well as poultry, proper management is required to obtain the beneficial use of this litter. Research by Williams, (2008) advocate that poultry litter and dry manure can be burnt in small furnaces to produce heat for farm utilization, or transported to central locations for combustion on a large scale for generating electricity. Technologies have risen as a result of efforts aimed towards safe disposal of poultry litter. Inclusive are technologies highlighted by Musa *et al.*, (2012), like converting broiler and turkey litters into bio oils and generating a gas to operate a pyrolysis unit. During these processes, the destruction of pathogenic microorganisms as well as the reduction of disease transmission chances are achieved. Additionally, poultry litter is used for electric generation in a number of plants in the US and in the UK.

Poultry litter is readily available from poultry farms and is a viable and renewable energy source with a heating value of approximately 9550 kJ/kg (Saidan *et al.*, 2017). Based on this interesting acquirable energy, the litter produced from poultry operations in Zambia can be used as a heat source for poultry houses during times of low temperature through combustion. In a study by Damasceno *et al.*, (2014) it was stated that maintaining temperatures inside the barn at appropriate levels can be solved by heating air up to the second or third week of rearing poultry using several energy sources like liquefied petroleum gas (LPG), coal and firewood. This adds to the costs of production. Due to the limited availability and the carbon dioxide emissions of fossil fuels which cause global warming, heat and power generation through the

combustion of biomass has become an issue of importance (Bogush *et al.*, 2018). On the other hand, using firewood for heat production causes deforestation as well as ecosystem disturbances since poultry production is a growing business in Zambia. The use of charcoal contributes to the high deforestation rate the country is experiencing which stands at 250 000-300,000 hectares per year placing Zambia among the top 10 countries with high deforestation rates in the world (Matakala *et al.*, 2015). Similarly, Tembo *et al.*, (2015) highlighted that Zambia's forest covers approximately 49 468 000 hectares of the land but regardless of this status the country is among top 10 greenhouse gas emitting countries due to deforestation. Hence this research focuses on substituting the aforementioned energy sources with poultry litter as the heat provider.

Space heating of poultry houses can be carried out through the direct combustion of poultry litter. However, with the increment in moisture content of the litter a decrease in the calorific value will be experienced. Thyagarajan *et al.*, (2013) reported that air dried samples have typical values of 13.5 GJ/ton as their calorific value being about half that of coal, although poultry litter is reported to have a low ash fusion temperature which can cause problems when using a conventional grate combustion system. Therefore, for the resourceful operation of a combustion facility, holding parameters such as combustion temperature, air mixture and moisture content within optimal specifications is a necessity and these must vary with combustion design.

2.3 Drying

Heat and mass transfer phenomena which include the heating of the product, vaporization of water from liquid state on the surface and within the product, diffusion of vapours, mixing the vapour with air and removing the moisture is known as drying (Abdel-Galil, 2007). The volume of the dried materials is reduced thus improving the efficiency of storage and transportation. Also, drying is influenced by air humidity, velocity and temperature (Agarry *et al.*, 2013). When drying manure, there is reduction in decomposition of chemical and biological activity thus preventing environmental problems associated with raw manure. Additionally, manure stickiness is reduced when drying hence allowing easy handling (Ghaly and MacDonald, 2012). Similarly, through drying, stability of manure is achieved, with it being odour free and being able to be conveyed with solid-handling equipment. (Abdel-Galil, 2007). Long

drying periods tend to increase the energy requirements for the production of a unit dry product as well as lead to final product of poor quality (Agarry *et al.*, 2013).

2.3.1 Open Sun Drying (OSD)

Drying under open sun using the solar radiations is a prehistoric practice, (Sahdev, 2014) in which products are spread in a thin layer on the ground and exposed directly to solar radiation (Navale *et al.*, 2015). There is partial reflection and absorption of solar radiation falling on the surface in which the absorbed radiations and surrounding air heat up the surface. Moreover, the moisture from the surface of the product is evaporated, by the produced heat, to the surrounding air although some of this heat is lost through long wave length radiation to the atmosphere and through the conduction to the ground (Sahdev, 2014). OSD is a widely known technique that reduces the moisture content of agricultural products preventing deterioration within a period of time and it is still practiced globally in spite of the incurred cons (Sobukola *et al.*, 2007).

During sun drying, products are placed on the ground where they are unprotected from contamination and attack by bacteria, infestation by insects, birds, animals and rodents and also it is laborious as the drying product layers have to be turned over and over again periodically to ensure undeviating drying (Abdulmajid, 2015). Solar energy is an important alternative source of energy and preferred to other energy sources because it is abundant, inexhaustible and non-pollutant which is also renewable, cheap, and environmentally friendly (Sobukola *et al.*, 2007) despite the lacking mechanisms for controlling the drying process which is heavily dependent on weather conditions (Abdulmajid, 2015).

2.3.2 Solar Tunnel Drying (STD)

When using these types of dryers, the drying process is controlled and the product being dried is protected from damage by insect pests, dust and rain. Also, comparing it to sun drying, the drying time of solar dryers is reduced by about 20 % and produces better quality dried products (Hegde *et al.*, 2015). They are mostly preferred since the product is dried in an enclosed and protected unit, under controlled conditions of temperature and air flow. In addition, solar dryers are classified as either active or passive in which active dryers have forced air circulation while passive models make

use of air buoyancy caused by temperature and pressure gradients (Abdulmajid, 2015). Solar tunnel dryers can have a solar storage system which is important in energy conversion and is responsible for a drying process even when direct sunlight is not available and this type of dryer has three parts: the collector, the drying cabinet, and the air blower (Mustayen *et al.*, 2014).

This type of dryer is constructed using plywood, stainless steel mesh, wooden skewers, clear glass and galvanized iron sheet (Hegde *et al.*, 2015). Higher temperatures are generated with lower relative humidity, lower moisture content and reduced spoilage during the drying process as compared to sun drying (Navale *et al.*, 2015). During drying, temperature losses are reduced to ambient levels using a glass cover, which is useful for increasing the product and chamber temperature (Mustayen *et al.*, 2014). One common drawback it shares with sun drying is its dependency on weather conditions and also they demand a greater labour input than traditional methods like loading and unloading of trays of produce (Kagande *et al.*, 2012). Figure 2.1 shows a forced convection Solar Tunnel Dryer (Kagande *et al.*, 2012).

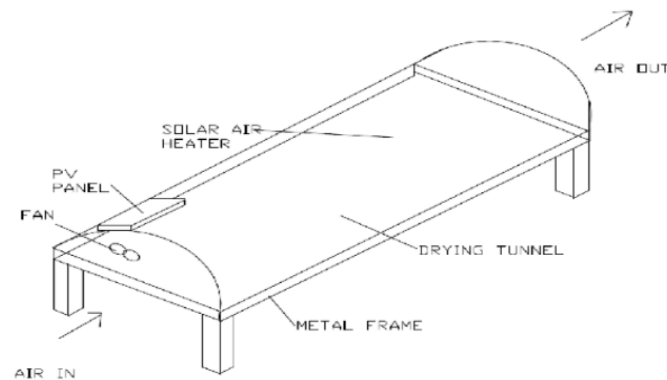


Figure 2.1 Solar Tunnel Dryer Configuration

2.4 Direct Combustion of Poultry Litter

Direct combustion is mostly used in developing countries. Demirbas, (2004) describes direct combustion as an ancient method of utilizing biomass and that it is operational in over 97% of the world's bio-energy production. Further report was provided that it is advantageous to use biomass as a combustion feedstock because of its high volatility as well as its high reactivity with the resulting char. A research by

Abdulrahman and Huisingsh, (2018) states that combustion is a simple and less technology demanding process for generating energy from biomass. In line with this, Weidemann *et al.*, (2015) highlighted that combustion involves the burning of material in the presence of oxygen to produce thermal energy. Additionally, it was reported that it is possible to use the resulting heat to generate other forms of energy including steam, hot water or hot air.

Co-firing and direct combustion processes are currently used for the burning of livestock and poultry manure. Comparatively co-firing is easier to achieve than direct combustion though a suitable coal-fired surrounding is required. Also impact on the surrounding environment are less through direct combustion as compared to co-firing (Yi *et al.*, 2018). The combustion of poultry litter seeks to produce heat and the possibility of providing this heat for other purposes. A mixture of straw, wood shavings and chicken manure describe poultry litter. In addition, the burning process is improved by the straw and wood shavings which also controls the moisture content of the litter. Also the litter has a high calcium content which act as a cleaning agent for gaseous emissions (Kelleher *et al.*, 2002).

Samboko *et al.*, (2016) reported that the poultry industry is a rapidly growing livestock subsector in Zambia and that in 2014 annual estimations of layer and broiler production were 1,005,910,434 tons and 372,285,812.16 tons respectively. It was also reported that due to power shortages and rationing, this could be disadvantageous to small-scale poultry farmers since alternative power sources are expensive. So, with the massive aforementioned numbers of broilers and layers, the litter acquired from the poultry houses can be used in direct combustion for space heating hence reducing heating costs and dealing away with disposal problems. The direct combustion of poultry is also advantageous as it results in the production of a nutrient rich ash which can be used as a fertilizer.

Affirmation by Perera *et al.*, (2010) describes the direct combustion of poultry litter as a process which generates hot flue gases for the production of steam coupled to turbine generator which in turn produce electricity. It was further reported that economically, direct combustion can be feasible on a large scale with the availability of raw materials. A report by Dalólio *et al.*, (2017) states that compared to other animal wastes, the heating value from poultry litter is relatively good although its ash

content has a low melting point because of the high presence of sodium and potassium. In addition to this, Perera *et al.*, (2010) confirmed that for the litter used in boilers during direct combustion its particle size can significantly affect the calorific value. It was further reported that larger particles of more than 150 μm had more calorific value (5 300 BTU lb⁻¹) and showed the lowest ash content in combustion.

2.5 Densification of Poultry Litter

Compacting residues into a product of higher density than the original raw material is known as densification or briquetting. Onuegbu *et al.*, (2011) explains briquetting as the process which can be implemented at high or ambient temperatures depending on the technology applied and requires high pressure. Additionally, some materials can be densified without the aid of a binder (binder less briquette) while a binder is added to some materials for adhesion purposes of biomass particles. In relation to this, Malatji *et al.*, (2011) pointed out that chicken litter may contain less or no lignin making it difficult to densify into stable briquettes. With this being said, cassava flour is chosen for the bonding effect of poultry litter. Cassava bonded briquettes have best physical and mechanical characteristics compared with other biomass bonded briquettes (Davies, 2015).

A research by FAO (1996) enlightens that densifying biomass embodies a set of technologies for converting biomass into fuel. Moreover, the compaction of residues primarily serves as a purpose for their use in energy production. In line with this Onuegbu *et al.*, (2011) highlighted that agricultural wastes and coal briquettes produce smokeless solid fuels. Extruding, pelleting and briquetting have been listed by Kaliyan and Morey, (2009) as three types of conventional densification processes. It was also reported that a screw or a piston compresses a raw material through a die to assume a cylindrical form in an extruder. Also, the usual diameters of extruded materials are between 20 and 100 mm. As also discussed by Malatji *et al.*, (2011), briquettes assume a size larger than pellets with a length of about 10-20 cm. Asian countries commonly utilize extrusion technologies for densifying biomass.

Densifying poultry litter makes it easy for transportation and storage, because of the uniform size, and increasing the calorific value thus providing possibilities for it to substitute charcoal. Similarly, as discussed by Balasubramani *et al.*, (2016) the utilization of waste biomass residues as briquettes is profitable and feasible since it is

converted to a more usable product. Rattanongphisat and Chindaruksa, (2011) carried out an experiment on bio-fuel briquette from durian peel and rice straw and found a higher heating value of 24.674 MJ/kg which is higher than the acceptable heating value in the market of 20.92 MJ/kg according to the Thailand Community standard. Based on this finding, biomass proves to be a possible substitute of wood fuel for space heating purposes. However, as reported by Malatji *et al.*, (2011) the combustion efficiency of the resulting briquettes depends on density, chemical composition and moisture content.

Primarily the briquetting of biomass focusses on utilizing forestry and agriculture residues instead of livestock and poultry (Yi *et al.*, 2018). Thus, using poultry litter briquettes will add value and hopefully to be of choice amongst the aforementioned preferred biomass briquette types since in some areas of the world it is now illegal to use it as a fertilizer.

2.5.1 Cassava Production in Zambia

Cassava, a shrubby tropical plant grown for its large, tuberous, starchy roots, is an important cash crop in tropical countries since it is drought resistant and less expensive to manage as compared to other crops (Zhang *et al.*, 2013). Cassava is mostly grown in Luapula, Northern, Western and North Western provinces in Zambia. However, its growing is encouraged in other parts of the country for food security reasons (Central Statistical Office, 2015). Cassava starch can be applied to food and nonfood industries since it has low gelatinization temperature, clarity, and bland taste (Zhang *et al.*, 2013).

In Zambia, the crop is one of the main food security crops, dominating the smallholder farming systems (Biratu *et al.*, 2018). Information by Central Statistical Office, (2015) states that 21,025 metric tonnes of dried cassava chips were sold country wide and 19,720 households selling cassava flour during the 2014/15 Season. Also, 4,669.6 metric tonnes of cassava flour were sold, while 144, 984 households had dry cassava in storage. Lastly, dried cassava chips of a total quantity of 17,191.2 metric tonnes were also in storage during the season.

2.6 Uses of Poultry Litter

Being a potential treasured source of energy, the thoughtful use of poultry litter may provide proceeds to the poultry industry when used as a source of energy. According to Baldin *et al.*, (2012) the utilization of biomass to generate electricity is a technology selected as an investment in the United States of America. Below are ways in which poultry litter is used;

2.6.1 Use as an Energy Source

Baldin *et al.*, (2012) reported that 200MW was acquired in the 70th decade which saw an increment of 8.4GW in the 90's and likewise 18GW in 2010. Further report was made that a plant is installed in the state of Minnesota in the United States to produce 18GW of energy with a burning capacity of 500 tons of litter per annum. In line with this, Weidemann *et al.*, (2015) also reported that the combustion of poultry litter is successfully implemented for the production of electricity in the United Kingdom and United States. Further additions were that the plants used are in medium range of energy generation (8-60 MW) and the larger end of this range (35-60 MW) being the newest plants.

In a research by Kelleher *et al.*, (2002) it was highlighted that in November 1993 a poultry litter fired power plant was officially opened by Fibropower, which was thought to be the first commercial plant of its type in the world at Eye in Suffolk UK. Likewise, 14 MWe is generated from this plant in which 12.5 MWe is supplied to a 33kV power line for distribution through local electricity networks after in-house use of electricity. By 2030, a plant in the state of Minnesota, US, intends to reach an output of roughly 100 GW of electricity through the burning of animal manure and agricultural residues (Baldin *et al.*, 2012).

2.6.2 Use as Livestock Feed

Due to its high nitrogen content, poultry litter can also be dried and used as a livestock feed. Affirmation from Ghaly and MacDonald (2012) provides knowledge that; in dry poultry manure there are adequate proteins, fat, iodine, cobalt crude fiber and digestible energy and thus can be used as a supplement with required nutrients for ruminants. Additionally, dried poultry manure was fed to ruminants as a digestibility experiment and an average net energy content of about 6400kJ/kg was obtained as well as an average protein content of about 300g/kg. Also, no alterations can be

effected on the feed conversion, daily gain, carcass quality or taste and smell of meat when dried poultry litter is used in fattening rations as confirmed from experiments on feeding young fattening bulls. Economically, the production of beef and dairy could be enhanced when poultry manure is used as a cattle feed as shown by the literature from Ghaly and MacDonald (2012), and also costs could be reduced since nutrients will be recycled while at the same time caring for the environment.

2.6.3 Composting

Sander *et al.*, (2002) defines composting as a sanitary and controlled decomposition of organic materials. It was also reported that an end product which is humus-like, odourless and spongy, and can be used as a soil supplement, is produced during suitable composting. Composting is a fast biodegradation process which takes 4–6 weeks to reach a stabilised material (Kelleher *et al.*, 2002). Amanulla *et al.*, (2010) states that composting includes anaerobic and aerobic processing and that it is a method that can be used to stabilize poultry litter before it is applied to land. It was further stated that composting is advantageous since it produces a material which is easy to handle due to reduction in volume, fly attraction, breeding and weed seed viability. Equally, pathogens are said to be destroyed through heat generation when composting.

2.6.4 Use in Biogas Production

Manure is the largest and cheapest resource for biogas production. According to Seadi *et al.*, (2008), Biogas is a combustible gas which consists of methane, carbon dioxide and minute amounts of other gases and trace elements. Additionally, biogas was initially produced and collected from a biological process for the first time in the United Kingdom in 1985. Miah *et al.*, (2016) reports that biogas is not only a most efficient and effective option for renewable energy but also an environmentally friendly practice. Moreover, it is a process with a series of biological steps where organic carbon is converted to carbon dioxide and methane. The production of biogas is through different substrates such as animal manure, industrial waste and dedicated energy crops.

Likewise, Unal *et al.*, (2015) confirmed that the biological step of biogas production, anaerobic digestion, has a positive outcome on the well-being of the environment as

it is usable for a relatively clean heat and power generation. In addition, the production of electricity, heat and fuel can be accomplished through biogas. In the early '70s, the energy crisis encouraged the use of renewable fuels, biogas from anaerobic digestion being inclusive. Furthermore, replacing fossil fuels in energy production drove to the utmost interest in biogas production which simultaneously provides green measures towards the treatment and recycling of animal manure and organic wastes (Seadi *et al.*, 2008).

The principal methods of thermochemical conversion of biomass are shown in Figure 2.2.

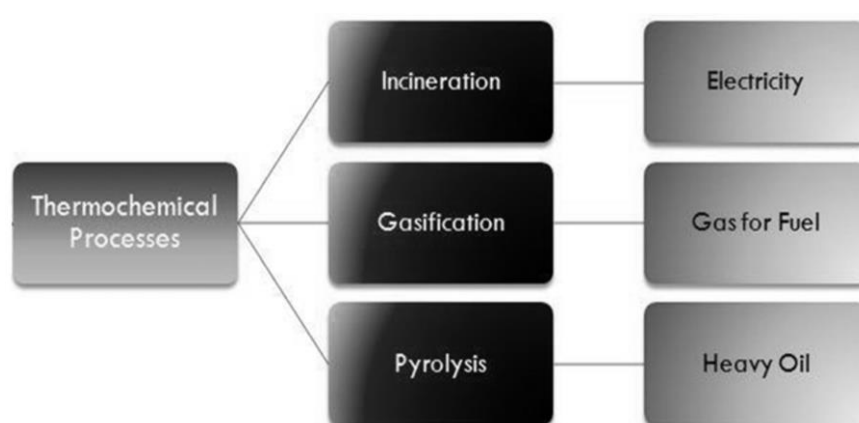


Figure 2.2 The principal methods of thermochemical conversion

Source: Unal et al., (2015)

As seen from Figure 2.2, pyrolysis and gasification represent refined thermal treatment methods as alternatives to incineration and are characterized by the transformation of the waste into product gas. The thermal destruction of biomass in the absence of or partial oxygen supply is termed pyrolysis resulting in the production of a hydrocarbon rich gas mixture, a carbon rich solid residue and an oil-like liquid, as seen in Figure 2.2. In addition, biomass undergoes a thermal treatment through pyrolysis to be converted to a more useful fuel (Demirbas, 2004). Gasification is defined by Taupe *et al.*, (2016) as an advanced technology which converts solid manure biomass through thermochemical treatment to a gaseous energy carrier called syngas or product gas under limited oxygen supply conditions. Gasification is the latest waste to energy conversion process and it enhances the efficiency as well as

lessening the investment costs of biomass electricity generation by the use of gas turbine technology (Demirbas, 2004).

2.7 Poultry Houses Heating Systems

The current heating systems being used in poultry houses either depend on electricity, LPG, diesel, coal and other renewable resources. Costs associated with the usage of the aforementioned fuels are considerably high thus affecting the economic efficiency of poultry houses. The prolonged usage of such fuels also cause harm to the environment through emissions like CO₂ which contributes vastly to global warming. Verification by Rajaniemi and Ahokas, (2015) provides support that the largest direct energy input is through space heating in broiler houses which significantly emits CO₂ when using fossil fuels for heating.

Since it is impossible for chickens to maintain their body temperatures, provision of artificial heat is essential so that chickens can maintain their body temperature with atmospheric temperature (Sable *et al.*, 2018). Similarly Damasceno *et al.*, (2014) highlighted that young birds require higher ambient temperatures because their thermoregulatory system is not fully developed making heating systems important in the poultry house. The availability of heat in poultry houses is through the use of mechanical systems which were an invention after natural ventilation. The energy-environment relation became key issues in building design hence leading to developments from natural ventilation system (Monghasemi and Vadiee, 2017).

Sources of heat in the poultry house encapsulate that of the birds, the heating system and the lighting equipment. Also, the heating system may be hot water piping, hot air blowers, gas burners or a combination of each (Hamilton *et al.*, 2016). In the same context, Coradi *et al.*, (2016) also highlighted that poultry houses include the usage of heaters such as, infrared, turbo gas, high-pressure and low-pressure firewood furnaces with preheated air, coal and firewood ones without air renewal. A big role is played by the requirement of energy in buildings and the range of the required energy for heating and cooling varies between 18% and 73% worldwide (Monghasemi and Vadiee, 2017).

Biofuel usage for heating has increased in broiler production e.g. in Finland and Sweden during the last years and their combustion is traditionally assumed to be CO₂ neutral. Similarly they reduce CO₂ emissions compared to the combustion of fossil fuels (Rajaniemi and Ahokas, 2015). The biofuel production chain causes emissions but that portion of the total GHG emissions is minor. Climate, bird mass, house type and insulation greatly affect heating energy consumption, that is, it is higher during cold seasons than warm seasons due to higher heat loss from buildings and ventilation. Moreover, energy demand is lower at the beginning of the rearing period due to the low ventilation rate (Bokkers *et al.*, 2010)

The relationship between the bird weight, outdoor temperature and energy requirement for heating purposes is presented in Figure 2.3. It shows that large amounts of heating power are needed when the weather is cold and the broilers are old. The largest heat power goes to heating the ventilated air, the requirement for which increases as the birds grow.

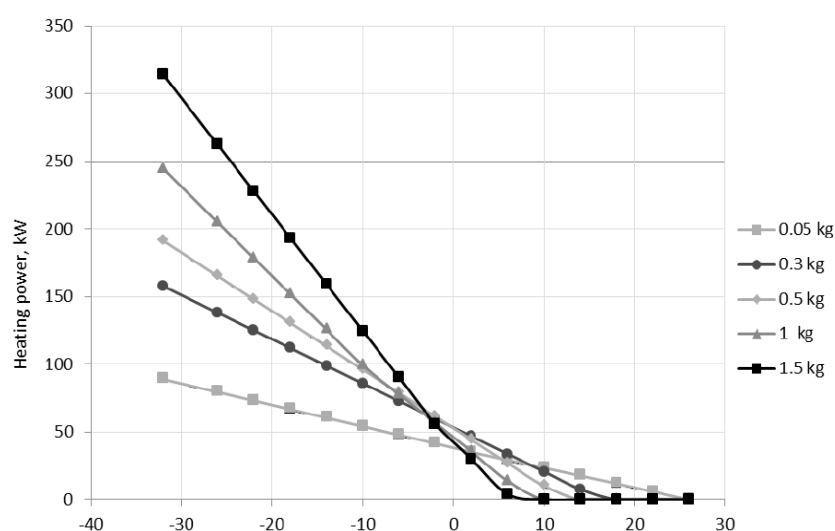


Figure 2.3 The relationship between bird weight, outdoor temperature and heat energy requirement.

Source: Rajaniemi and Ahokas, (2015).

The supply of this heat in a poultry house is through several mechanisms and equipment which vary from the smallest and simplest, to the largest, and complicated and are as follows:

2.7.1 Gas Brooder

Shown in figure 2.4, this is a fully automated system which requires less man power and uses LPG for heat production. It is composed of sensors, exhaust system and control panel. The major setbacks are that as the prices of LPG increase, the working costs will as well increase and also initial and operating costs are high making it unaffordable to small holder farmers. Equally, lack of electricity in rural areas makes this system unsuitable for usage in rural areas. With the stated setbacks, usage of such a system will present high operational costs.

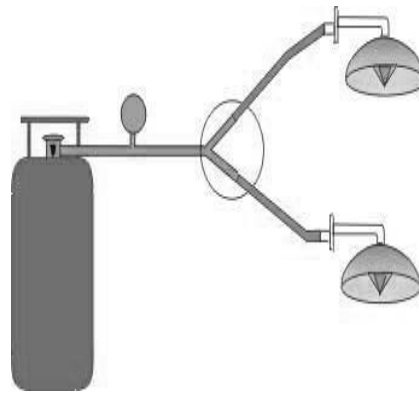


Figure 2.4 Gas Brooder

2.2 Pot Charcoal Brooder

This type of brooder is made of mud and its sides have holes for entrance of oxygen and heat exit thus preventing smoking (Ayalew *et al.*, 2012). Pot charcoal brooder is cheap and readily available and uses charcoal as a heat source which makes it applicable in rural areas (Sable *et al.*, 2018). In other setups, an empty pot is used to cover a pot which contains burning charcoal in a mouth-to-mouth configuration to retain the heat and flames of the fire. Additionally, the environment is warmed by the heat which radiates from the pot (Roy *et al.*, 2018).

Ayalew *et al.*, (2012) conducted an experiment on 60 chickens by using pot charcoal brooder, positive control electric brooder and negative control brooder over 15 days and no deaths of chicken brood by pot charcoal brooder were recorded compared to the other two. This type of heater, shown in Figure 2.5, presents a friendly and suitable

way for warming a poultry barn, as it is cheap. One major setback is that it uses charcoal which is the main cause for deforestation.



Figure 2.5 Pot Charcoal Brooder

2.3 Kerosene Brooder

This type of brooder, shown in Figure 2.6, is able to heat approximately 1000 birds with 40 liters of kerosene per day and plays a vital role in rural areas. Lamps use kerosene as a fuel and provides heat to the environment (Sable *et al.*, 2018). One lamp will be able to provide heat for 50 chicks and the requirement of lamps will increase with the number of birds making it an expensive method since kerosene is expensive. Therefore, this method may be suitable for the brooding of a small number of chicks. Heat is reduced or increased through the use of a knob on the lamp.



Figure 2.6 Kerosene Brooder

2.4 In-Floor Heating Concept

This system has an electric under-floor heating system and underground pipes which transfers heat to the floor through conduction, convection and radiation as shown in Figure 2.7. Also, both heating and cooling can be implemented with this system thus an external boiling and cooling system is a requirement if both are incorporated in this system (Sable *et al.*, 2018). Large amounts of heat can be distributed in a bigger area producing a microclimate near the floor where animals are surfaced and this reduces energy consumption rather than heating air in the whole building. Conversely, heat demand can rise when the night cools off and once required temperatures are achieved, cooling the concrete is slow resulting in unfavourable conditions to animals (Wheeler Amec Foster Mining and Metals Americas, 2016). Usage of such a system may present high energy costs since it is complicated and requires a lot of electricity.

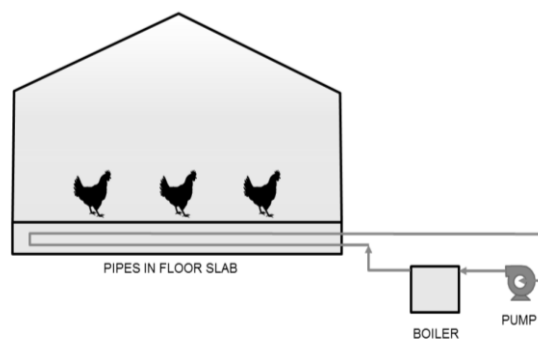


Figure 2.7 In-floor Heating Concept

2.5 Convective Heating System

As seen in Figure 2.8 this system has a hot water fin pipe or a straight pipe which is not finned and is usually applicable to areas where extreme cold periods lead to higher heat demands. Additionally, cold air is pre-heated, as it enters the barn, by a heat source (hot water pipe) which is located close to the fresh air supply thus preventing cold temperatures while improving distribution of air. Also, since hot water is used to provide and transfer heat, this system becomes effective because water has four times the thermal capacity of air. Adversely, more time is required to cool down the barn when warm weather returns (Wheeler Amec Foster Mining and Metals Americas, 2016).

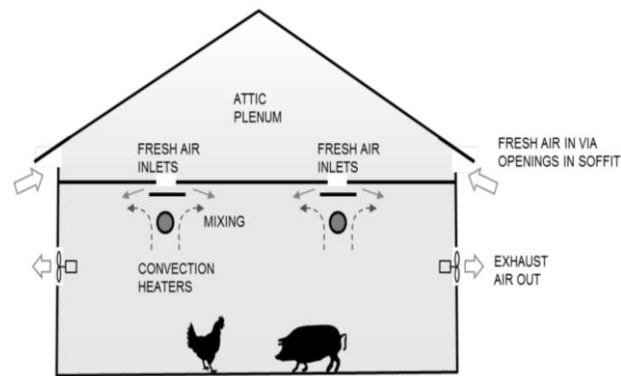


Figure 2.8 Convective Heating System

2.6 Radiant Tube Heater

This system uses electricity and transfers heat over a large area through radiation. When using this system disadvantages like temperature variations along the tube, discontinuous power supply (causing heating inconveniences) and overheating can be experienced (Sable *et al.*, 2018). The radiation tube heaters are hung near the ceiling and radiate heat downward to the bird and litter pack as shown is Figure 2.9. Also, the tubes have reflectors above them which protect the ceiling and reflect rays coming from the top of the tube to the house floor.

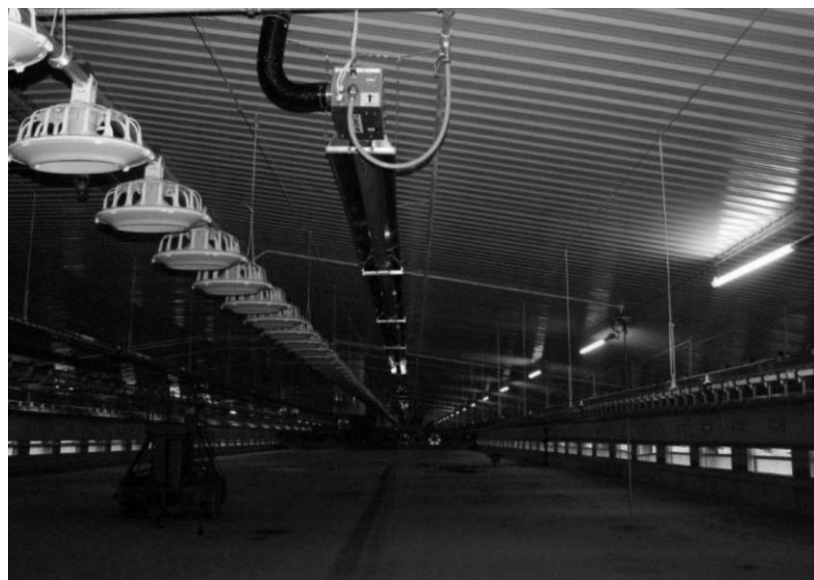


Figure 2.9 Radiant Tube Heater

2.8 Closing remarks

The significance of solar drying for manure utilization has been extensively explained in this chapter. Poultry Litter, its combustion and how it has been used as well as different methods for warming poultry houses have also been emphasized in this chapter. It can be pointed out that drying is an essential process when using litter for combustion. The next chapter outlines the Methodology utilised for this research.

CHAPTER 3 METHODOLOGY

This chapter entails of how the research was carried out to meet the set objectives and the information on the experimentation site. Figure 3.1 shows a flow chart representing the procedures carried out in this research.

As seen in Figure 3.1, Poultry Litter was collected from the University of Zambia's poultry house through random sampling. After sampling and collection, poultry litter paste was made by mixing with cassava flour and water then densified using a hand mincer. The paste was densified to make Poultry Litter Briquettes which had their initial moisture content determined using an oven. The briquettes were then either solar tunnel dried or open sun dried then direct combustion and calorific value determination followed. Detailed explanations of all the steps in the figure follows after it.

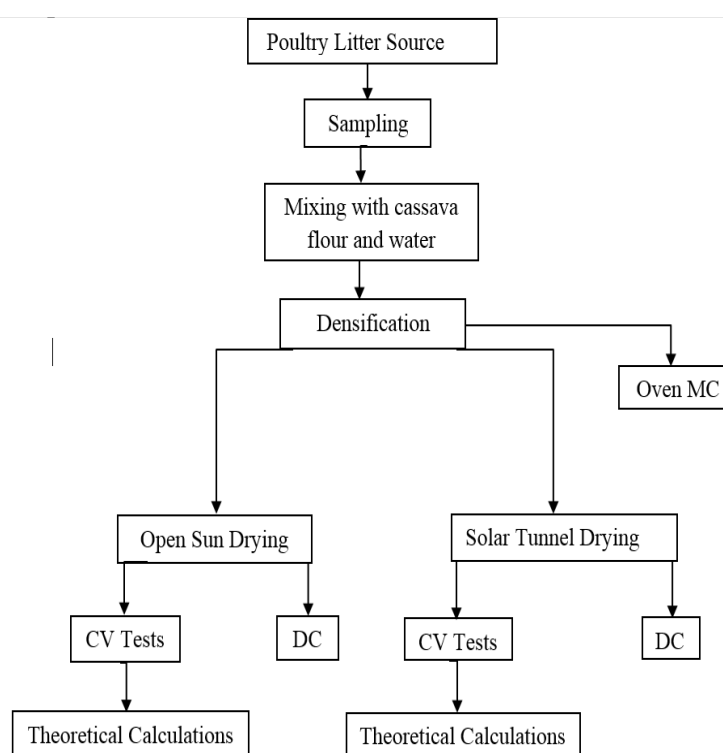


Figure 3.1 Flow chart showing the procedure for direct combustion of poultry litter

3.1 Poultry Litter Sampling and Collection

Poultry litter was obtained from a broiler house at the University of Zambia. The litter, which had a bedding of wood shavings, was collected from the floor of the broiler

house which accommodated 3000 chickens. The collected litter was fresh and not subjected to any treatment on the farm. Sampling was done according to the age of litter at week 4, 5 and 6. Sampling was done randomly at different points in the poultry house then mixed and stored in a 25kg sack. From each age, two sacks which contained 20kg of the litter were obtained and prepared for the experiment.



Figure 3.2 The sampling, collection and how the PL was stored.

After the poultry litter sampling and collection as shown in Figure 3.2, the litter was stored in a sack which was tied and stored at room temperature before the poultry litter briquettes were made. The same procedure was done for all the samples at different ages.

3.2 Management of the Poultry House

The broiler chickens were reared in a 17.5 m by 7.5m poultry house made of concrete bricks and a roof of iron sheets which had no ceiling. The poultry house had curtains on its sides for ventilation. For space heating, the poultry house was equipped with 50 infrared lights, each rated at 75 Watts which kept chickens warm for three to four weeks. Figure 3.3 shows an image of incubation of broiler chicks.



Figure 3.3 The incubation of broiler chicks at week 1

Table 3.1 shows the feeds which were fed to the broiler chicks through the rearing period as well as the vaccines which were used against pests and diseases common to broiler chickens. Such information is necessary in case of a difference in the calorific value obtained from the used litter compared to the one from literature. Management plays a vital role in characteristics of the obtained litter.

Table 3.1 Feeds and vaccines for Broilers from the UNZA poultry house

Broiler Feeds	Drugs/Vaccines used
Broiler Starter Feed	Enrazag
Broiler Grower	Aprolium
Broiler Finisher 1	Vitamins Stresspack
Broiler Finisher 2	Amyrite
	Virukill
	Vetfluid
	Vaccines Gumboro
	Newcastle
	Antibiotics Dioxycip 50%

3.3 Making the Poultry Litter Paste

The collected poultry litter was hand crushed so that it could blend easily when mixed with the binder and water. In this case cassava flour was used to bind the crushed poultry litter. Cassava flour has proven to provide strength to briquettes as well as providing an efficient combination (Teixeira *et al.*, 2010). The poultry litter paste was prepared by adding cassava flour and water to PL in a bucket and mixed by hand until a homogenous mixture was formed as shown in Figure 3.4. For the poultry litter sample at week 4, 800g of cassava flour was added to 1800g of poultry litter and mixed with a volume of water of 2400ml. The feed-flour ratio was 44.44%. 1800g of poultry litter at week 5 was mixed with 300g of cassava flour and 1600ml of water. The feed-flour ratio of this age was 16.67%. At week 6, 250g of cassava flour was mixed with 1800g of poultry litter and 1600ml of water and yielded a feed-flour ratio of 13.89%.

A research by Altun *et al.*, (2004) reported a ratio of 10%, by weight of biomass, for both water and flour to be used. The same ratio was used in this research but resulted in a less coherent paste. Therefore, flour and water was added in bits to poultry litter until a homogenous paste which could easily be molded was formed. The volume of water to be used was measured using a 2L jug. Poultry litter and cassava flour were measured using a digital balance (Mettler, Model PE3000, accuracy $\pm 0.1\text{g}$). Cassava is categorized as an organic binder. In advocacy to this type of binder, Zhang *et al.*, (2018) reports that it has good bonding performance, high crush strength and drop test strength and decompose easily at high temperatures. Cassava flour was chosen as a binder because it is readily available in Zambia and also because of the good characteristics as obtained from different sources. Figure 3.4 shows how poultry litter paste was prepared. More instruments are shown in Appendix A.



Figure 3.4 Procedure for making the PL paste

From figure 3.4, weighing to mixing in a bucket is shown. The dish was put on a digital scale which was tarred and poultry litter was put on it together with cassava meal and later transferred to the mixing bucket to make the paste.

3.4 Densification of Poultry Litter

Before briquettes were made, the paste was allowed to settle for 15 minutes so that a uniformly compacted product could be produced. A stainless-steel hand mincer, primarily intended for sausage making, was used to make PL briquettes. A hand mincer was selected for this research for the densification of biomass. The reason for selection is because of its low cost, continuous production, simplicity and convenient making it even suitable for usage in less developed areas. The parts which were meant for the pressing and stuffing purposes of sausage were removed. The rest of the body which has a feeding hopper, worm (screw) and a handle were not altered. A fabricated nozzle which was made of galvanized iron sheet was then fitted where these parts were removed to serve as a die where PL briquettes were pressed through.

The nozzle had a length of 11cm and a diameter of 25mm producing briquettes of 25mm after the compacting process. Since the paste was highly viscous, it was pressed into the feeding hopper by hand so that it could be pushed by the rotating worm to the die thus forming briquettes. The worm rotates as the handle is being rotated. As the worm rotates, the paste is pushed forward into the barrel. The continual rotation of the worm acts as a pump causing compression at the far end of the barrel which

consequently forces the paste through the die. A continuous briquette was formed which was measured to 10cm by a ruler and cut using a knife. Hence briquettes formed had a length of 10cm and a diameter of 25mm. Briquettes were made at night prior drying experiments and they were stored in tied plastic bags so that they do not lose their moisture.



Figure 3.5 The hand grinder which was used to densify PL to make PLB

The side view shows the handle, feeding hopper, the nozzle and the top view which shows the worm (auger) which compresses the PL during briquetting. The continual briquette is also shown in Figure 3.5 which was cut into 10cm lengths to make multiple poultry litter briquettes.

3.5 Oven Moisture Content

Before the drying experiments were carried out, the initial moisture content of the samples of PL briquettes was determined by oven drying at 70°C for 5 hours at an interval of 30 minutes. After 5 hours the samples were left to dry overnight to evaporate all the moisture and were removed in the morning. The samples were dried in an oven (Jeio Tech, Model ON-02G, accuracy $\pm 0.5\%$). Three samples were put in 3 different petri dishes which had their weight predetermined by a digital weigh balance as shown in Figure 3.6. The recorded weight with time was that of the samples combined with the one for petri dishes. The weight of the petri dishes was subtracted from the total weight (weight of dish+ PL sample) when calculating the initial moisture contents of the three samples. The moisture contents were then added and the average was found. The initial moisture content was calculated using equation 3.1.

$$MC_{wb} = \left(\frac{W_i - W_f}{W_i} \right) * 100 \quad 3.1$$

Where; MC_{wb} is the initial moisture content of the sample in wet basis (%), W_i is the initial weight of the poultry litter sample (g) and W_f is the final weight of the poultry litter sample (g).



Figure 3.6 The instruments which were used for the moisture content determination.

3.6 Drying Experiments

This study was carried out at the University of Zambia in Lusaka with coordinates; Latitude 15.3°S; Longitude 28.3°E. The university's Department of Agricultural Engineering workshop was used to run the experiments.

3.6.1 Solar Tunnel Drying

A portion of the samples of poultry litter briquettes from different ages of weeks were dried using a solar tunnel dryer placed in an open and flat area. The dryer was situated in a true north position which, was found by the use of a phone compass, so that it got placed at a site with full exposure to sunshine. The dryer, shown in Figure 3.7, had 4 legs and 3 components which were the collector unit, drying unit and the chimney unit. The drying unit had an absorber plate made from Galvanized Iron sheet which was painted black to increase its solar absorptivity and it was covered with a transparent 200 μm polythene sheet which extended to the drying unit.

The drying unit was made from the same material as the collector unit and was in line with the collector unit. It had a removable wire tray which served the purpose of holding the PLB during the drying period. Air exiting the drying unit was reheated in the chimney unit which was made from a 0.3mm galvanized iron sheet painted black. The chimney unit was perpendicular to the drying unit. The solar tunnel dryer in Figure 3.7 is described in detail by (Cherotich and Simate, 2016).



Figure 3.7 The side and rear views of the solar tunnel dryer

A multi-channel data logger (Campbell Scientific, Model CR1000) was connected to the solar tunnel dryer to record the temperatures, relative humidity and solar radiation during the period of drying as shown in Figure 3.8. The data logger had three thermocouples (Campbell Scientific, Model T108, accuracy ± 0.2 °C) for temperature measurements which were capable of recording temperatures of range -5 and +95 °C, a pyranometer (Kipp and Zonen, Model CM11, accuracy $\pm 0.5\%$) placed on a horizontal flat surface near the dryer to measure solar radiation, a relative humidity probe (Model HMP60-L) placed outside the dryer to measure ambient relative humidity and the ambient temperature and was capable of temperature and humidity ranges of -4 °C to 60 °C and 0 to 100 % respectively.

The three thermocouples were used to measure temperatures at points of; exit of the collector unit (T_{CU}), exit of the drying unit (T_{DU}) and at the exit of the chimney unit (T_{CH}). The relative humidity probe was use to record the ambient temperature (T_{AM}) outside the dryer and was placed in an open area and not exposed to the sun at all times. The data logger automatically recorded readings every 10 seconds which were accessed by connecting the data logger to the laptop.



Figure 3.8 Experimental set-up of the solar tunnel dryer and the equipment.

(1) collector unit, (2) drying unit, (3) bare flat- plate chimney Unit, (4) solar pyranometer (5) Humidity probe (6) Laptop and (7) Data logger

These experiments were conducted during the months of June and July to compare the drying rates of PLB from the solar tunnel dryer (STD) to those of a control experiment of open sun drying (OSD). The drying experiments through a solar tunnel dryer and open sun were run simultaneously and were later compared under direct combustion.

The dryer and the equipment were arranged as illustrated in the experimental set-up in Figure 3.8 and the experiments were conducted between 09:00 h and 16:00 h due to abundance of solar radiation during this period. The PLB which were made and stored in plastic bags the night before the drying experiment commenced were weighed using a digital balance and loaded on a wire tray on the day of the experiment. From the tray, only 3 PLB were chosen as samples which would be used for recording the moisture loss. The PLB were taken from the fore front of the tray, middle and at the far end of the tray. Each of the briquettes was marked so that recording could be precise.

The PLB had an average initial weight of 63g, length of 10cm and a diameter of 25mm. The wire tray was loaded with 45 PLB and then put in a STD in the drying unit. By 09:00hrs all equipment was assembled and the experiment started. The T_{CU} , T_{DU} , T_{CH} , T_{AM} and the solar insolation were recorded through the data logger throughout the day until 16:00hrs and was downloaded to the computer. For recording moisture loss of the selected PLB, weight loss was taken at an interval of 30 minutes for the first 6 hours then hourly until a fairly constant weight was achieved using a digital balance.

During drying, the recorded weights were converted to moisture contents by using Equation 3.2.

$$MC_t = 100 - \left(\frac{W_0 (100 - MC_0)}{W_t} \right) \quad 3.2$$

Where; MC_t (% w.b.) is the moisture content at any time t , W_0 (g) is the initial weight of sample before solar drying, MC_0 (% w.b.) is the initial moisture content of sample before solar drying and W_t (g) is the weight of the sample at any time t in the course of solar drying.

The drying experiments took 4-7 days for each age depending on the weather conditions. At the end of each experimental day, the wire tray which was loaded with the PLB, as shown in Figure 3.9, was removed from the STD and put inside the workshop on the floor. The following day the weight loss experienced overnight was recorded and the experiment continued likewise.



Figure 3.9 How PLB were stored (in plastic bags), weighed and how they were placed in the STD for the process of drying.

Figure 3.9 shows the storage of poultry litter briquettes and their orientation during drying in a solar tunnel dryer. The compartment painted black is a collector unit whereas the drying unit is where the wire tray with PLB is placed.

3.6.2 Open Sun Drying

The PLB were loaded in the wire tray, shown in Figure 3.10, and the same procedure from STD was implemented for OSD. For OSD the parameters of interest were the solar insolation and the ambient temperature. Both the OSD and STD were carried out on the same days simultaneously for each age. After drying was completed for each age, the PLB were stored in paper bags as they awaited direct combustion. The paper bags were labeled the number of days it took for drying, the age and the drying method. The average moisture contents (% w.b.) of the PLB in the STD and OSD were then plotted against drying time on the same graph to allow comparison.



Figure 3.10 Sun drying of PLB

The PLB were put on a wire tray and put in an open area from 09:00hrs to 16:00hrs.

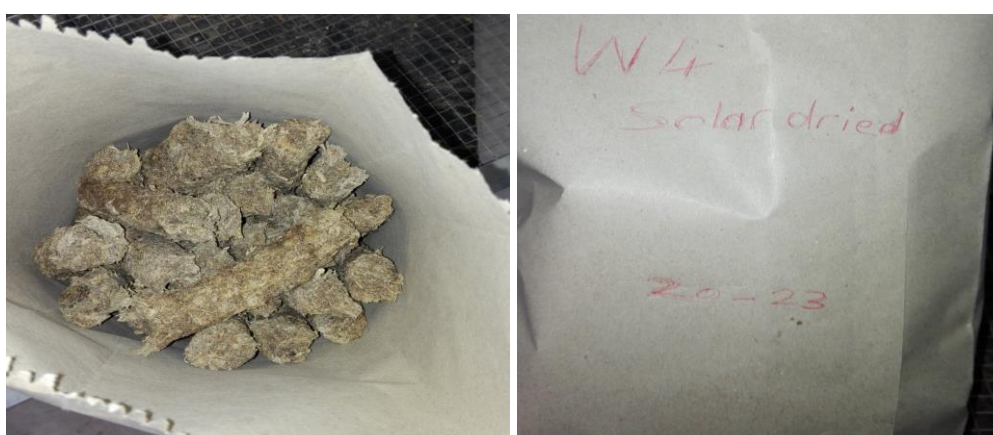


Figure 3.11 How PLB was stored after drying

Figure 3.11 shows how the poultry litter briquettes were stored after drying. The paper bag containing the poultry litter briquettes was put in another paper bag so that the briquettes do not gain moisture as the process of drying was carried out for other ages.



Figure 3.12 Dried PLB from weeks 4, 5 and 6 respectively

From figure 3.12 it can be noted that the manure content increased as the weeks lapsed as seen from the darkening colour of the PLB from week 4 to week 6.

3.6.3 Developing Thin Layer Drying Models to Predict Drying of PLB Under the STD and OSD

The recorded weight loss of the 3 samples of PLB at any time from the drying experiments were added and their average found and used for calculating the moisture loss in wet basis at any time. The wet basis moisture contents were then converted into dry basis using Equation 3.3.

$$mc_{db} = \frac{100 \times mc_{wb}}{100 - mc_{wb}} \quad 3.3$$

Where; mc_{db} is the moisture content %d.b and mc_{wb} is the moisture content %w.b. From the moisture content results, the Moisture Ratio (MR) was calculated. The calculations were done by converting moisture content in dry basis to moisture ratios using Equation 3.4 (Daud and Simate, 2017; Agarry *et al.*, 2013).

$$MR_t = \frac{mc_t (\% d. b)}{mc_0 (\% d. b)} \quad 3.4$$

Where; MR_t is the moisture ratio at any time t , mc_t is the percentage dry basis moisture content at any time t , and mc_0 is the percentage dry basis initial moisture content before the solar drying of samples.

The MR results from Equation 3.4 were fitted into 12 empirical thin layer models using Microsoft Excel in-built Solver in non-linear regression mode. The primary criterion for selecting the best moisture ratio equation that defines the drying curves of PLB were the correlation coefficient (R^2), the reduced chi-square (χ^2) and the root mean square error (RMSE) (Sobukola *et al.*, 2007; Daud and Simate, 2017). The correlation coefficient (R^2) gives the prediction ability of the model and its value varies between 0 and 1, where the value closest to 1 represent the greatest fit. The reduced chi-square (χ^2) is used to determine the goodness of fit and the lower its value, the better the goodness of fit. The root mean square error (RMSE) gives the deviation between the predicted and experimental values and it is required to reach zero. The aforementioned parameters used for selecting the drying model were calculated as follows;

$$R^2 = \frac{\sum_{i=1}^N (MR_{i,exp} - MR_{i,exp,mean})^2 - \sum_{i=1}^N (MR_{i,pre} - MR_{i,exp})^2}{\sum_{i=1}^N (MR_{i,exp} - MR_{i,exp,mean})^2} \quad 3.5$$

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{i,exp} - MR_{i,pre})^2}{N - n} \quad 3.6$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N (MR_{i,pre} - MR_{i,exp})^2 \right]^{\frac{1}{2}} \quad 3.7$$

Where; MR_i is the 'i'th experimental moisture ratio, MR_i is the 'i'th predicted moisture ratio, $MR_{i,mean}$ is the mean value of experimental moisture ratios, N is the number of observations, and n is the number of constants in the moisture ratio equation.

Table 3.2 Thin Layer Drying Models

Model	Name of model	References
$MR = \exp(-kt)$	Newton	Ayensu (1997), Liu and Bakker-Arkema (1997), Tiris et al. (1994)
$MR = \exp(-kt^n)$	Page	Doymaz (2004c), Karathanos and Belessiotis (1999), Park et al. (2002), Sun and Woods (1994)
$MR = \exp[(-kt)^n]$	Modified Page	Overhults et al. (1973), White et al. (1978, 1981)
$MR = \exp(-(kt)^n)$	Modified Page	Demir et al. (2004), Ozdemir and Devres (1999), Panchariya et al. (2002)
$MR = a \exp(-kt)$	Henderson ve Papis	Chhinnan (1984), Pal and Chakraverty (1997), Rahman et al. (1998)
$MR = a \exp(-kt) + c$	Logarithmic	Doymaz (2004a), Lahsasni et al. (2004c), Yagcioglu et al. (1999)
$MR = a \exp(-kt) + b \exp(-k_1t)$	Two-term	Dandamrongrak et al. (2002), Madamba et al. (1996), Soponronnarit et al. (2001)
$MR = a \exp(-kt) + (1 - a) \exp(-kat)$	Two-term exponential	Ertekin and Yaldiz (2004), Midilli and Kucuk (2003), Sharaf-Eldeen et al. (1980)
$MR = 1 + at + bt^2$	Wang ve Sing	Chen and Wu (2001), Panchariya et al. (2002), Wang and Singh (1978)
$t = a \ln(MR) + b(\ln(MR))^2$	Thompson	Madamba et al. (1996), Paulsen and Thompson (1973), Thompson et al. (1968)
$MR = a \exp(-kt) + (1 - a) \exp(-kbt)$	Diffision approximation	Ertekin and Yaldiz (2004), Kassem (1998), Togrul and Pehlivan (2003)
$MR = a \exp(-kt) + (1 - a) \exp(-gt)$	Verma et al.	Verma et al. (1985), Yaldiz and Ertekin (2001)
$MR = a \exp(-kt) + b \exp(-gt) + c \exp(-ht)$	Modified Henderson ve Papis	Karathanos (1999), Karathanos and Belessiotis (1999), Togrul and Pehlivan (2003)
$MR = a \exp(-kt^n) + bt$	Midilli et al.	Ertekin and Yaldiz (2004), Midilli et al. (2002)

Source: Okyay and Ertekin, (2006); Togrul and Pehlivan, (2002)

3.7 Direct Combustion (DC) of Poultry Litter Briquettes

The experiment was carried out to determine the amount of heat produced from the poultry litter briquettes and its distribution.

One kilogram of poultry litter briquettes from different weeks were each ignited in a brazier which had an average of 32 holes on its sides to allow for oxygen entrance during burning and aid with complete combustion. A digital balance was used to measure the quantity of PLB to be combusted in the brazier. It comprised of dimensions; Diameter=8 cm and Height=65 cm. Two space-heating braziers of same dimensions and made of the same material (mild steel) were bought from City Market and were adopted for the application of the methodology of this study. They were used interchangeably to allow for cooling off for the next experiment step.

For each experimental run, the brazier was covered with a lid so that the heat produced did not escape through the mouth of the brazier. During direct combustion, Thermocouples were placed around the brazier at different distances to record the amount of heat being emitted from the combustion of poultry litter briquettes. Heat distribution was measured at distances of 30 cm, 60 cm and 90 cm from the brazier. A measuring tape was used to determine these distances. A high temperature digital multimeter (Dynatek 9030a) coupled with a temperature probe, (ANSI Code: Type K, accuracy $\pm 1.1^\circ\text{C}$ or $\pm 0.4\%$) with the capability of recording temperatures from -

270°C to 1300°C, was used to record the brazier surface temperature as time lapsed at an interval of 10 minutes.

A probe connected to the high temperature thermometer was tied around the brazier with a wire. A data logger, connected to a laptop, was used to record the ambient temperature and air temperatures from the thermocouples as a result of the combustion of poultry litter briquettes. This experiment was carried out at the Department of Agricultural Engineering workshop in an open space. From the onset of combustion, pieces of paper were used to help with the combustion of poultry litter briquettes. The brazier was taken outside so that the smoke from the startup of burning could be released. It was left for a period of 30 minutes before the experiment was started. The initial temperature of the surface of the brazier was recorded. The experiments took place at different times of the day. Charcoal was combusted and used as a control. After direct combustion, the ash from all the ages was weighed on a digital balance to determine the ash content of poultry litter briquettes according to weeks as well as that of charcoal.



Figure 3.13 How igniting PLB and the control (charcoal) was carried out.

A is the weighing of the PLB samples, B are the braziers used and charcoal, C and D are the incineration of PLB.

They samples were weighed, put in a brazier then ignited outside and left until there was no smoke produced from the burning.



Figure 3.14 The side and top view of the experimental set up for the DC process throughout the experiment for all ages of PLB and charcoal

As seen in figure 3.14, the thermocouples were tied around bricks so that they stayed in fixed positions. Thermocouple (1), (2) and (3) were placed at distances 30cm, 60cm and 90cm from the brazier respectively. Photo 4 shows a brazier with a lid, photo 5 a digital multimeter (high temperature thermometer) and photo 6 a high temperature probe tied on the surface of the brazier with a wire. A piece of brick was used to keep the probe intact on the surface. Also shown is a laptop (7) connected to a data logger (8) and a humidity probe (9) which was used to measure ambient temperature.



Figure 3.15 The DC of PLB after the smoke was released and the final product which is the ash

The ash was weighed and its content was calculated from its ratio and the combusted PLB. The ash content was calculated using the following equation;

$$\text{Ash Content (\%)} = \left(\frac{M_{\text{ash}}}{M_{\text{briquette}}} \right) * 100 \quad 3.8$$

Where; M_{ash} is the weight of the ash in grams, $M_{\text{briquette}}$ it the weight of the dried PLB in grams.

3.8 Calorific Value Determination

The experiment was carried out to determine the calorific value of PLB at different week ages.

All fuels have a physical property termed calorific value or heating value defined as the amount of heat released during a combustion process which is regularly expressed in kilocalories or kilojoules of one kg or liter of fuel (Bouabid *et al.*, 2015). A bomb calorimeter was used experimentally to determine the heating value of PLB. This apparatus measures the enthalpy change between reactants and products. The PLB samples were taken to Zambia Bureau of Standards (ZABS) for calorific value determination. An IKA C5003 calorimeter system was used for this experiment.

Apparatus: Bomb calorimeter, Thermometers and accessories, calorimeter vessel (C5003), electric balance scale, sample holder, ignition fuse, pelleting machine, calorimeter accessories, ignition circuit, controller and crucible liner.

Reagents: Benzoic acid pellets, distilled water and oxygen.

3.8.1 Bomb Calorimeter Methods

The higher heating value of poultry litter briquettes, was determined by the bomb calorimetric method according to standard test method for gross calorific value of coal and coke (D 5865-03). From the dried poultry litter briquettes, few samples were taken for calorific value experimentation. The dried sample was ground to powder where about 1 gram of it was weighed with an electronic balance and pelleted then placed in a crucible. A crucible with a pellet containing about 1 gram of poultry litter briquette was inserted into the bomb. After closing the bomb, it was filled with oxygen (purity 99.99%), (Acar and Ayanoglu, 2012) under a pressure of 3 bars.

The bomb was placed in the calorimetric equipment filled with water and the sample was ignited electrically. The resulting increase of the water temperature allows the calculation of the higher heating value of the sample. The heat capacity of the calorimeter was determined using benzoic acid pellets as a standardizing material. The higher heating value of the sample was then calculated by multiplying the temperature rise in the calorimeter (water jacket) by the heat capacity of the calorimeter determined from benzoic acid.

The sample, contained in a crucible with cotton thread, was placed inside a bomb calorimeter surrounded with distilled water as shown in Figure 3.16.

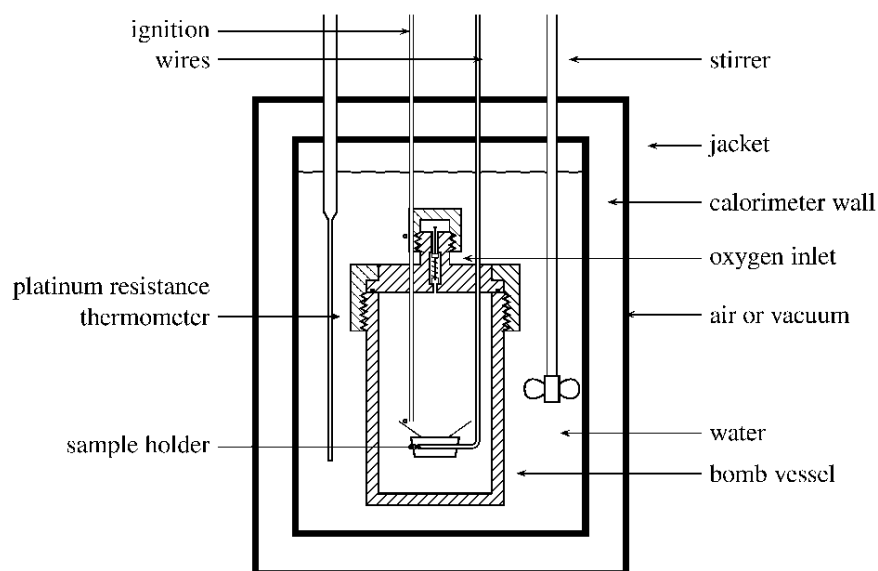


Figure 3.16 The cross section of a bomb calorimeter

3.9 Experimental Design

Statistical analyses, Analysis of Variance (ANOVA) Single Factor, were performed with Microsoft Office 2016 Excel and SPSS v 16.0 to determine the significant differences between the treatments. Differences were considered significant at $p < 0.05$. There were 6 treatments of PLB and a control being charcoal under a factor of produced heat.

3.10 Closing Remarks

This chapter described in detail the methodologies adopted in this work. Specifically, methods employed during sampling, densification, drying, direct combustion, ash content and calorific value determination were described. The next chapter presents the results obtained in this work.

CHAPTER 4 RESULTS AND DISCUSSIONS

This chapter presents the results and discussions of the study. The chapter covers the following in detail; the briquetting of poultry litter, poultry litter briquettes drying experiments, thin layer modelling of poultry litter briquettes, direct combustion of poultry litter briquettes, calculations of the ash content of poultry litter and calorific value determination of poultry litter briquettes.

The ratio of a binder (cassava flour) to feed (PL) is shown in Figure 4.1. Raw data is shown in Appendix B.

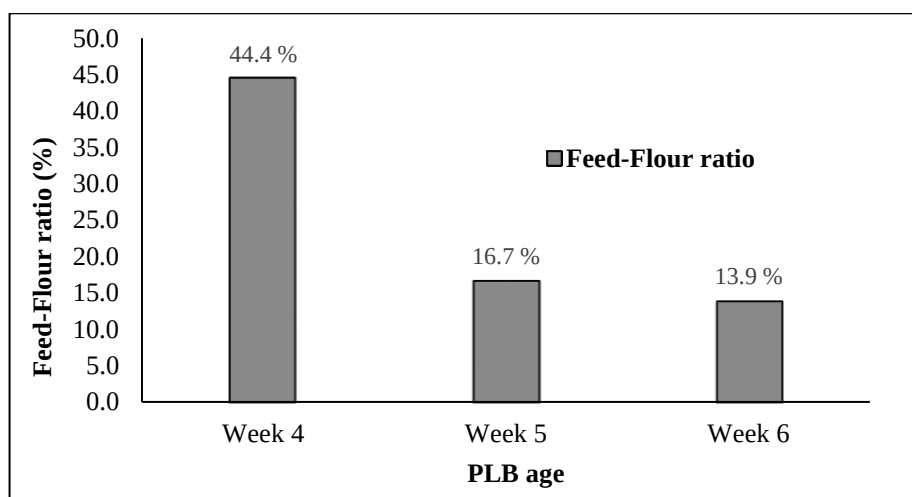


Figure 4.1 Feed (PL) to flour ratio during the process of making the briquettes

Figure 4.1 clearly shows that as weeks lapse, the amount of cassava meal needed for binding purposes reduces. Before making the briquettes, PL at week 4 had more of the bedding (wood shavings) and these reduced the stickiness of the litter. For adherence to be successful, more of cassava meal was needed which amounted to 44% of the weight of PL used for making briquettes. As chickens grow, more manure is produced which then results in less requirement of the binding material. In this manner, PLB at week 5 reduced the requirement of cassava flour to 16.7% of the weight of PL and likewise 13.9% of cassava meal was required at week 6.

The binder requirement at week 6 is almost a quarter to that at week 4, making PL at week 4 the highest consumer of the binder. So, at week 4, more binder was also needed not only because PL at that age was lacking plasticity but the hand grinder as well was not able to produce sufficient pressure for the bonding of the litter at this particular week. A clear description on the feed to flour ratio according to different week ages

is given in chapter 3.3. Binders are good because they produce a consistent mix of briquettes which will burn at a steady rate.

4.1 Drying of PLB

A total of 6 drying experiments were conducted. Each week comprised of two drying experiments which were run concurrently being that of STD and OSD. The drying time ranged from 31 hours to 55 hours. Open sun drying took more time across all weeks as compared to solar tunnel drying, shown in Figure 4.3, due to the fact that it was winter and there was less sunshine, the weather was not consistent as well. There were days in which there was total cloud cover which delayed the process of drying. The experiments were run 7 hours each day and then continued the following day until a uniform weight loss was recorded.

4.2 Initial Moisture Content of PLB Samples

Poultry litter was wetted to an average initial moisture content of 60.93% during the making of poultry litter briquettes. The moisture content was determined through the use of an oven and the resulting moisture content fell in the range of 50-85% for agricultural biomass as reported by (Malatji *et al.*, 2011).

4.3 Air Temperatures and Solar Radiation During Solar Tunnel Drying and Open Sun Drying of Poultry Litter Briquettes

Figure 4.2 shows the variation of solar insolation with ambient temperature and air temperatures in the dryer on four different drying days. From Figure 4.2, maximum and minimum values of the measured parameters from different days are shown for the months of June and July respectively. From each month a day with maximum values and the other with minimum recorded values were used.

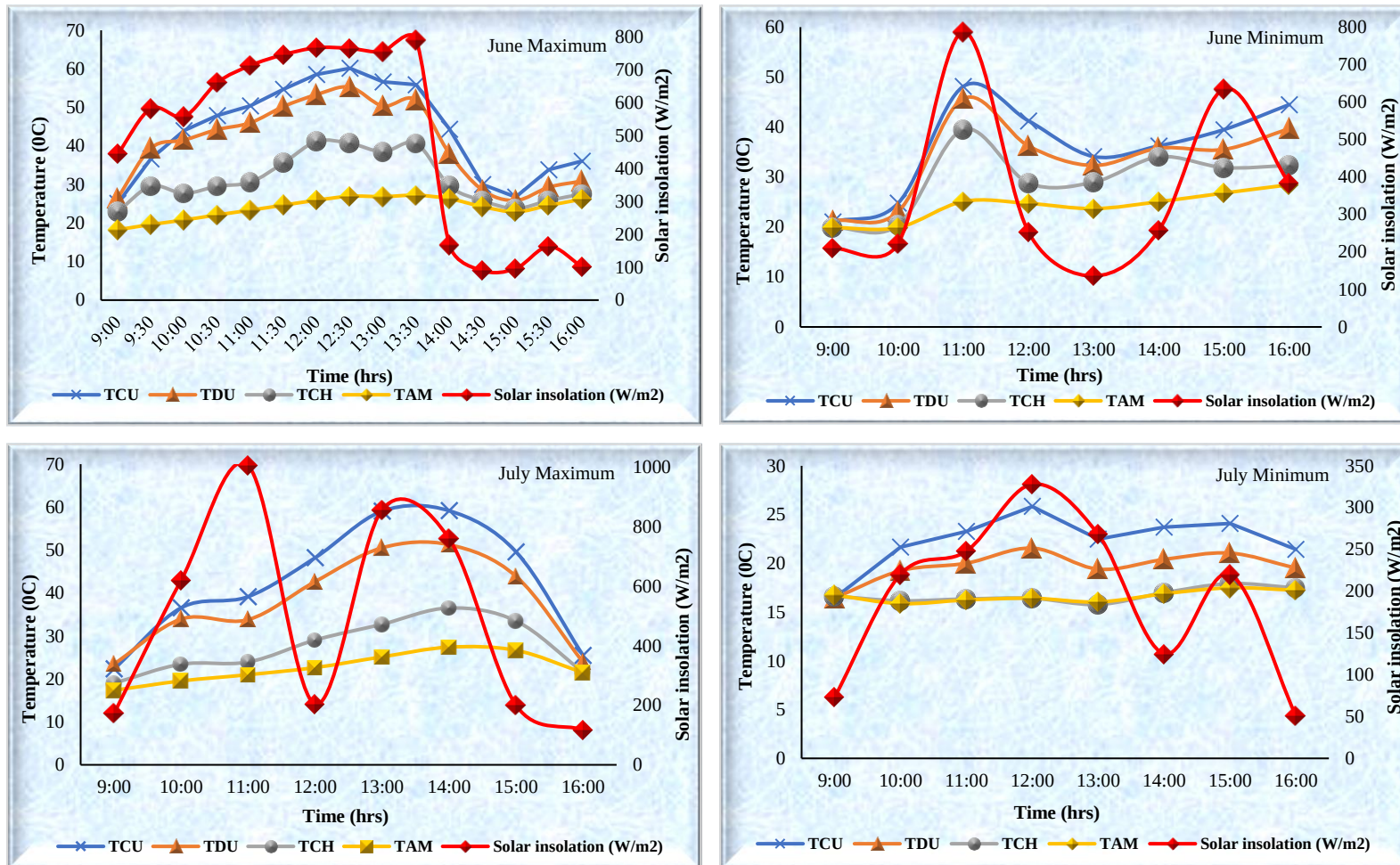


Figure 4.2 Maximum and minimum solar insolation and air temperatures recorded on four different drying days for the months of June and July

T_{CU}, T_{DU}, T_{CH} and T_{AM} = temperature of the collector unit, drying unit, chimney exit and of the ambient air.

During both drying days, solar insolation generally increased progressively between 9:00 hours to 13:00 hours and then subsequently decreased gradually up to 16:00 hours. Comparisons to this trend are from Cherotich and Simate, (2016) in the drying of mango slices using a Natural Convection Solar Tunnel Dryer where solar insolation continuously increased from 9:00 hours to 11:00 hours and then subsequently decreased to 16:00 hours during a typical drying day in November 2015 in Zambia; Daud and Simate, (2017) in the drying kinetics of sliced pineapples in a solar conduction dryer in Zambia where solar radiation increased from 9:30 to 13:30 hours and then decreased gradually up to 16:30 hours on a typical drying day in February and Hegde *et al.*, (2015) in which a research for a design, fabrication and performance evaluation of solar dryer for banana was carried out at India, Bengaluru in March and reported that solar insolation increased by the day from 9am to 1pm and started to drop until 5pm.

As seen from Figure 4.2, an increase in solar insolation generally resulted in an increase of air temperature at different points in the dryer and the ambient between 9:00 hours to 13:30 hours. Likewise, the opposite was manifested in the figure for both points from between 11:00 hours and 13:30 hours up to 16:00 hours. This trend in the variation of solar radiation with temperature can be attributed to the fact that the production of heat is through the absorption of solar energy on the collector unit (which was painted black to increase its capacity to absorb solar energy) as well as the briquettes, which were being dried. Hence air entering the collector unit is heated and flows to the drying unit. Also, the polyethene plastic cover which was used on the solar tunnel dryer reduced heat losses to ambient and likewise this increased the air temperature in the drying unit. It can also be seen from Figure 4.2 that the air temperature rise and fall closely follow the insolation curve except at the end of the day. This is due to the heat storage effect caused by the polyethene cover which helped maintain the air temperatures even though the insolation drastically drops (Hegde *et al.*, 2015).

It is worth noting that even though solar insolation radically drops from between 11:00 hours to 13:30 hours, the ambient air temperature does not drastically drop as it absorbs the heat radiated by the ground and from the surrounding objects. The highest magnitudes of solar insolation, T_{AM} , T_{CU} , T_{DU} and T_{CH} recorded in June and July were between 11:00 hours and 13:30 hours both from the maximum and minimum

category. Solar radiation considerably decreased continuously after 14:30 as a result of increasing cloud cover and shading within the vicinity of the dryer. Minimum values of the measured parameters were experienced because of cloud cover with no or less sunshine. The maximum solar insolation recorded in June was 790W/m^2 compared to maximum of 1005W/m^2 recorded in July. The solar insolation values recorded in June were more constant compared to those acquired in July which were fluctuating. The resulting maximum recorded T_{AM} , T_{CU} , T_{DU} and T_{CH} in June and July were 27°C , 60.15°C , 55.25°C and 41.17°C ; 27.4°C , 59.16°C , 51.25°C and 36.52°C respectively.

The measured temperatures are not very different from each other. Comparing the air temperature in the collector unit to the ambient temperature from the two months, it can be pointed out that the air was heated by an average of 32.5°C which decreased to 26.1°C in the drying unit and subsequently reduced to 11.6°C in the chimney exit. On the minimum category of measured parameters, July had low values of solar insolation being 328W/m^2 and T_{AM} , T_{CU} , T_{DU} and T_{CH} of 17.49°C , 25.83°C , 21.56°C and 17.48°C while June had a solar insolation value of 787W/m^2 which eventually dropped to 253W/m^2 and T_{AM} , T_{CU} , T_{DU} and T_{CH} of 28.45°C , 48.14°C , 45.69°C and 39.52°C . In relation to the ambient temperature, the air temperature in the collector unit was heated to an average value of 14°C which reduced to 10.6°C in the drying unit later on reducing to 11.1°C in the chimney exit recorded on the minimum category of the drying period. The graphs comparing the results of moisture loss with time obtained from open sun drying and solar tunnel drying across all weeks is shown in Figure 4.3.

Figure 4.3 shows the drying curves of poultry litter briquettes from different weeks. Raw data is shown in Appendix C.

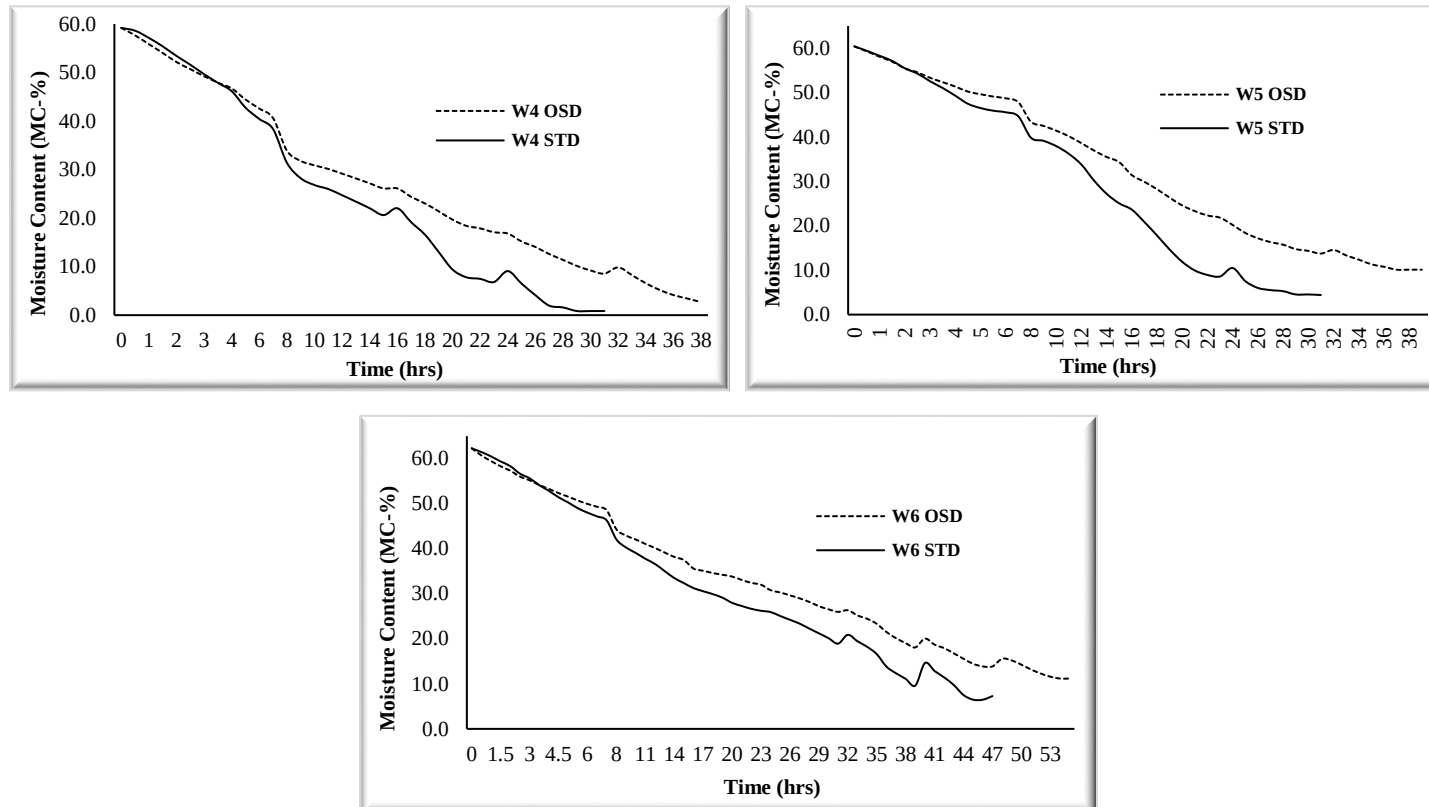


Figure 4.3 The moisture loss of PLB across weeks and drying methods against time

W; 4, 5 and 6 = week 4, 5 and 6. OSD = Open Sun Drying and STD = Solar Tunnel Drying

From Figure 4.3, poultry litter briquettes (PLB) at week 4 were dried from an initial moisture content of 59.2% (wb) to a final moisture content of 0.8% to 2.7% (wb) in a period of up to 35 hours, hence drying took place in the falling rate period. For drying experiments of poultry litter briquettes using a solar tunnel dryer, moisture content was reduced from 59.2% to 0.8% (wb). The duration for the removal of 58.4% (wb) was 31 hours which was 7 hours faster than that of open sun drying. It took 38 hours for the drying of poultry litter briquettes under open sun drying which took more time as seen from the graph. Elapsed drying time at week 5 was more or less similar to those at week 4 although the moisture loss under open sun drying was slower than that at week 4.

At week 5 poultry litter briquettes were dried from an initial moisture content of 60.4% (wb) to a final moisture content between 4.4% and 10.1% (wb) in a period of up to 39 hours. The briquettes dried through a solar tunnel drier took 31 hours to reach a final moisture content of 4.4% (wb) which was 8 hours faster than that of open sun drying. Under open sun drying 39 hours elapsed to reach a final moisture content of 10.1% (wb). Drying of PLB at week 6 was slow taking more hours than other weeks. A maximum of 49 hours was taken to complete the drying experiment. This was due to the change in weather conditions since there was low solar insolation and the humidity levels were high. Initial moisture content of 62.3% (wb) was reduced to final moisture content of a range of 7.3% and 11.1% (wb) through solar tunnel drying and open sun drying respectively. Solar tunnel drying took 47 hours whereas open sun drying took 55 hours.

From all weeks, solar tunnel drying was faster than open sun drying. Reasons are that the moisture content lost from PLB is attributed to the increasing solar radiation intensity received at the collector unit which causes a temperature rise of the entering ambient air thus increasing its ability to absorb moisture from the PLB in the dryer. Abdulmajid, (2015) affirmed that surfaces of the product being dried and that of the dryer absorb the heat generated by solar radiation and transfers it to the air inside the collector unit which then flows over the product being dried thus causing drying. The impediment of using OSD for the drying of PLB was that they will either absorb or desorb moisture depending on the relative humidity. The drying rates are even lower when the vapour pressure in the briquettes becomes equal to the partial water pressure in the surrounding air. From the drying curves (Figure 4.3), there were periods where

moisture was gained at night while awaiting drying the next day. Moisture gain is seen by a slight rise in the drying curve instead of a continual drop. This may have been due to high humidity levels in the night because the PLB had less moisture than the surrounding air.

Generally, drying rates were highest during the first 9 hours of drying, when the moisture content was greatest. This applied to the drying of PLB across all weeks. Navale *et al.*, (2015) verified that higher moisture reductions are incurred during the course of initial drying stages due to evaporation of free moisture from the outer surface layers and reduced to internal moisture migration from the inner layers to the surface. Kagande *et al.*, (2012) also carried out an experiment on the Design and performance evaluation of solar tunnel dryer for tomato fruit drying in Zimbabwe and found out that upon the recommencement of drying, the drying rate increased due to the fact that moisture migrated to the surface of tomatoes overnight. Observations made from the results in Figure 4.3 are in line with this finding as the PLB moisture loss was rapid, up to 20 hours of the duration of drying experiment. Based on the results, the heat evaporated the moisture from the PLB, in STD, thus promoting natural circulation of drying air and can be concluded that drying was at high temperature and low humidity as compared to OSD.

4.4 Thin Layer Drying Modelling

The results from the thin layer modelling are shown in Tables 4.1 and 4.2 Subsequent to drying, Microsoft Excel 2016 built in solver was used to fit the moisture ratios of PLB in twelve thin layer drying equations. It was observed that all twelve models, except for the Wang ve Sing model, gave a considerably good fit for all the PLB samples both from STD and OSD. The correlation coefficient (R^2) ranged from 0.993 to 0.999 for the 11 accurate drying models, reduced chi-square (χ^2) ranged from 0.026 to 6.496E-14, root mean square error (RMSE) from 0.011 to 0.063 and for the Wang ve Sing drying model (R^2) ranged from 0.216 to 0.794, (χ^2) from 1.711 to 540.618 and RMSE from 0.330 to 4.916. The variation with time of experimental moisture ratios of different PLB from all week ages are shown in Figure 4.4. Drying experiment at week 4 was faster taking 38 hours, followed by week 5 which took 39 hours of drying resulting with drying at week 6 being the slowest yielding a drying duration of 55 hours.

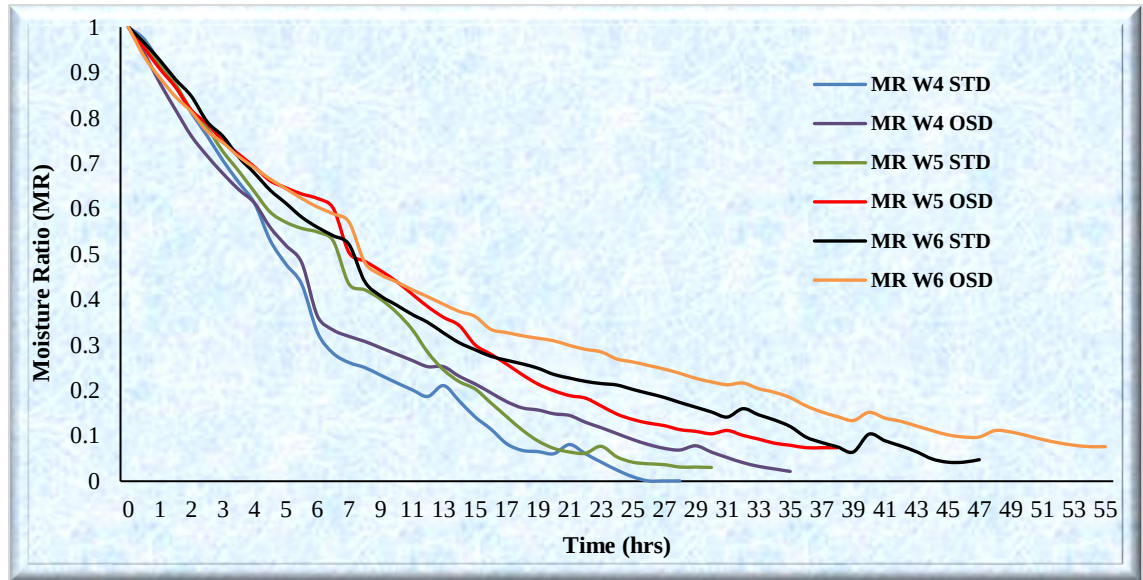


Figure 4.4 Variation of moisture ratio with drying time for PLB

From the mentioned information, the order of best fit was not similar for the PLB samples based on all the statistical parameters (χ^2 , R^2 and RMSE) used to select the best model as depicted in Table 4.1 and 4.2. Among all drying models, The Logarithmic model was the most consistent for all the samples of PLB either from STD or OSD except for week 4 which was from OSD which fitted best in the Two Term Exponential model. The Logarithmic model had R^2 ranging from 0.993 to 0.999, χ^2 from 6.496E-14 to 1.3626E-11 and RMSE from 0.0130 to 0.0294. The Two Term Exponential had R^2 ranging from 0.996 to 0.999, χ^2 from 7.07E-06 to 0.0007 and RMSE from 0.0156 to 0.0357.

Table 4.1 Thin layer drying modelling results for PLB (STD)

MODEL NAME	SOLAR DRYING									
	WEEK 4			WEEK 5			WEEK 6			
	correlation	RMSE	χ^2	correlation	RMSE	χ^2	correlation	RMSE	χ^2	ORDER
Page	9.963E-01	2.39E-02	2.55E-02	9.970E-01	2.40E-02	4.54E-04	9.955E-01	2.63E-02	7.75E-04	6
Henderson and Pabis	9.971E-01	2.37E-02	1.46E-05	9.970E-01	2.46E-02	5.64E-04	9.894E-01	4.17E-02	4.56E-03	8
Logarithmic	9.972E-01	2.36E-02	3.46E-12	9.976E-01	2.11E-02	1.36E-11	9.946E-01	1.30E-02	6.50E-14	1
Two term exponential	9.971E-01	2.45E-02	3.08E-05	9.971E-01	2.47E-02	3.92E-04	9.959E-01	2.61E-02	6.63E-04	4
MR model (Newton)	9.971E-01	2.46E-02	1.62E-05	9.971E-01	2.47E-02	3.81E-04	9.920E-01	4.79E-02	2.75E-03	9
MR model (Wang ve Sing)	7.941E-01	3.57E-01	1.76E+00	8.342E-01	3.30E-01	1.71E+00	2.162E-01	3.87E+00	2.99E+02	12
MR model (Modified Page)	9.971E-01	2.46E-02	1.67E-05	9.971E-01	2.47E-02	3.92E-04	9.920E-01	4.79E-02	2.81E-03	8
MR model (Midilli-kucuk)	9.973E-01	2.30E-02	2.01E-06	9.977E-01	2.07E-02	3.51E-07	9.963E-01	2.33E-02	1.95E-06	2
MR model (Diffusion approximation)	9.972E-01	2.34E-02	2.89E-06	9.971E-01	2.47E-02	4.03E-04	9.978E-01	1.90E-02	8.38E-05	3
MR model (Verma et al)	9.972E-01	2.34E-02	6.08E-06	9.970E-01	2.45E-02	5.37E-04	9.899E-01	4.04E-02	3.60E-03	10
MR model (Modified Henderson and Pabis)	9.974E-01	2.28E-02	3.30E-04	9.970E-01	2.45E-02	5.87E-04	9.983E-01	1.61E-02	2.82E-05	5
MR model (Two Term)	9.972E-01	2.36E-02	6.18E-05	9.970E-01	2.45E-02	5.53E-04	9.899E-01	4.04E-02	3.67E-03	11

Table 4.1 and 4.2 show all the twelve drying models with their corresponding statistical parameters used for determining the best drying model which defines the drying behavior of PLB from both STD and OSD. The logarithmic model was chosen as it gave the lowest reduced chi squared (χ^2), Root Mean Square Error (RSME) as well as the highest correlation (R^2). The order of best fit is defined by the descension of numbers, that is, 12 represents the least accurate model having Lowest R^2 , highest χ^2 and RMSE while 1 represents the most accurate model having Highest R^2 , lowest χ^2 and RMSE. The highlighted digits differentiate drying models appropriate to PLB at that particular week and drying method.

Table 4.2 Thin layer drying modelling results for PLB (OSD)

MODEL NAME	SUN DRYING									
	WEEK 4			WEEK 5			WEEK 6			
	correlation	RMSE	χ^2	correlation	RMSE	χ^2	correlation	RMSE	χ^2	ORDER
Page	9.942E-01	1.979E-02	2.051E-06	9.99E-01	1.28E-02	3.90E-05	9.97E-01	1.81E-02	6.28E-05	6
Henderson and Pabis	9.942E-01	3.038E-02	9.302E-04	9.99E-01	1.54E-02	1.02E-04	9.87E-01	4.22E-02	2.87E-03	8
Logarithmic	9.942E-01	3.038E-02	9.302E-04	9.99E-01	1.42E-02	3.63E-13	9.93E-01	2.94E-02	1.59E-12	1
Two term exponential	9.975E-01	1.988E-02	7.065E-06	9.99E-01	1.56E-02	2.59E-04	9.96E-01	3.57E-02	1.09E-06	4
MR model (Newton)	9.952E-01	3.901E-02	6.212E-05	9.99E-01	2.16E-02	1.49E-04	9.91E-01	6.33E-02	1.62E-04	9
MR model (Wang ve Sing)	7.872E-01	3.674E-01	2.369E+00	4.36E-01	1.29E+00	2.87E+01	2.18E-01	4.92E+00	5.41E+02	12
MR model (Modified Page)	9.952E-01	3.901E-02	6.363E-05	9.99E-01	2.16E-02	1.52E-04	9.91E-01	6.33E-02	1.65E-04	8
MR model (Midilli-kucuk)	9.973E-01	2.019E-02	1.388E-05	9.99E-01	1.25E-02	2.49E-07	9.98E-01	1.74E-02	2.24E-06	2
MR model (Diffusion approximation)	9.977E-01	1.863E-02	3.185E-05	9.99E-01	1.13E-02	5.85E-06	9.99E-01	1.36E-02	1.94E-05	3
MR model (Verma et al)	9.951E-01	2.775E-02	5.456E-04	9.99E-01	1.39E-02	5.12E-05	9.89E-01	3.79E-02	1.93E-03	10
MR model (Modified Henderson and Pabis)	9.977E-01	1.862E-02	4.408E-05	9.99E-01	1.11E-02	9.80E-07	9.99E-01	1.35E-02	1.30E-05	5
MR model (Two Term)	9.951E-01	2.775E-02	5.594E-04	9.99E-01	1.39E-02	5.43E-05	9.89E-01	3.79E-02	1.97E-03	11

The drying behavior of PLB, which is best defined by the Logarithmic drying model, is shown in Figure 4.5. A plot of experimental MR and Logarithmic model predicted MR against drying time from week 5 STD, week 5 OSD, week 4 STD and week 6 OSD respectively, was made and is presented in Figure 4.5. More graphs of a plot of experimental MR and other models is shown in Appendix D.

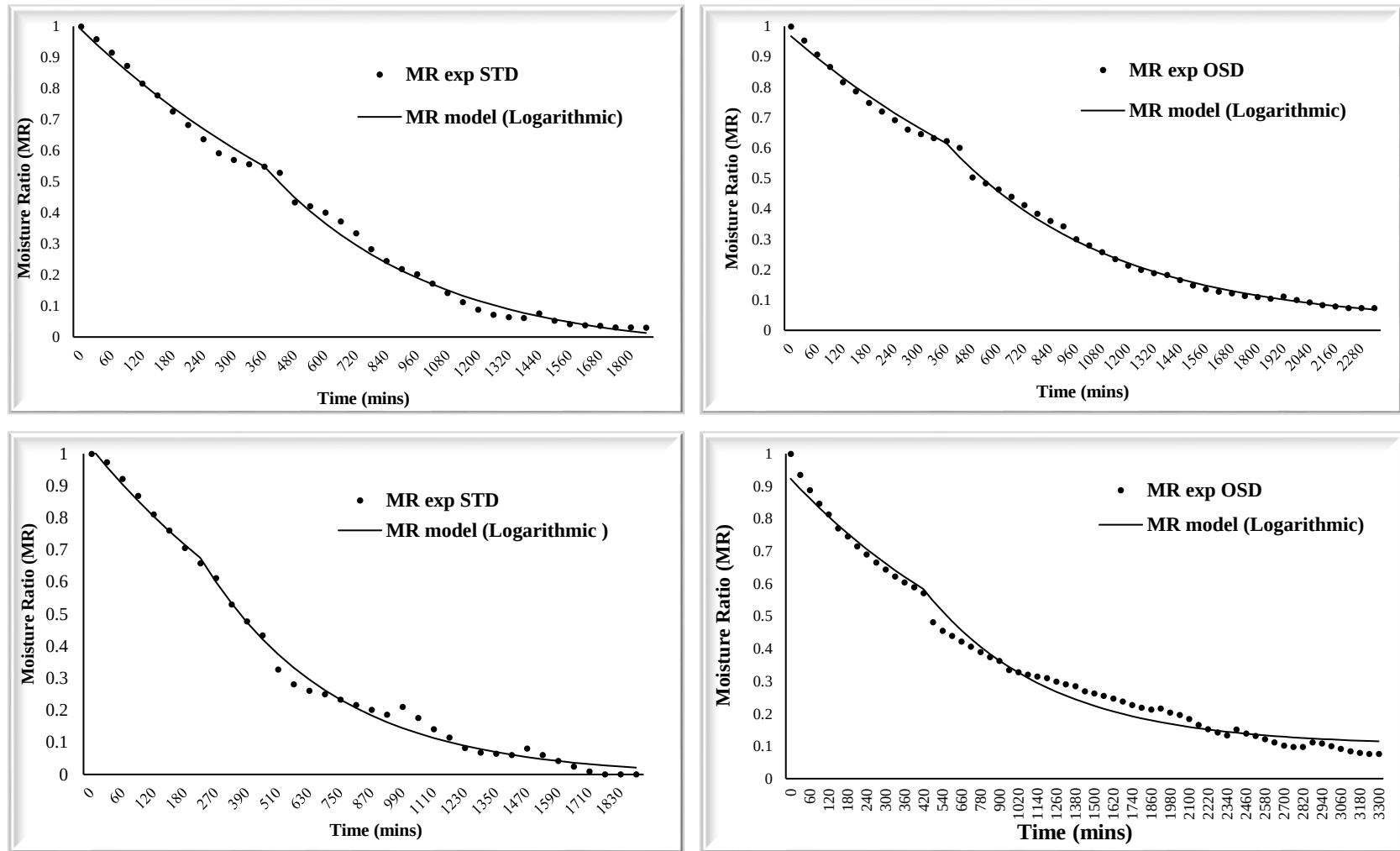


Figure 4.5 Variation of experimental MR and model MR for week 5 STD, week 5 OSD, week 4 STD and week 6 OSD respectively against time

The drying behavior of PLB at week 4 for OSD followed a drying model of Two Term Exponential shown in Figure 4.6. A plot of experimental MR and Two Term Exponential model predicted MR against drying time from week 4 OSD is presented in Figure 4.6.

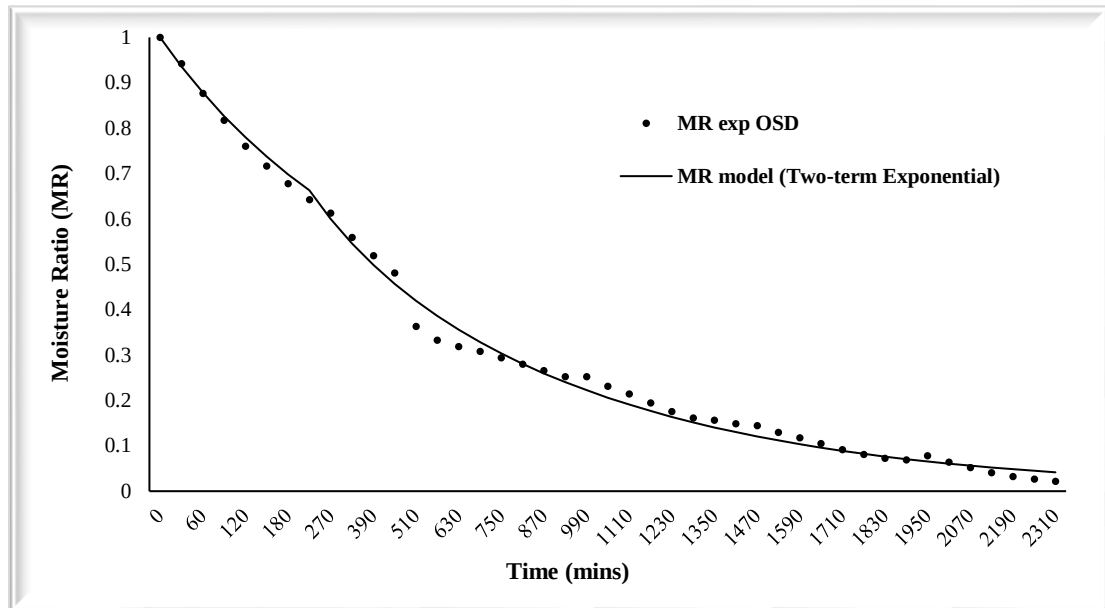


Figure 4.6 Variation of experimental MR and model MR of week 4 OSD against time

With the data obtained from plotting the two accurate models, it can be observed that the predicted and experimental MR compare well, indicating that the Logarithmic and Two Term Exponential model can predict with a high degree of accuracy the MR of PLB as drying progresses under similar conditions shown in Figures 4.5 and 4.6. Since the Logarithmic method was the most dominant across all weeks regardless of the drying method, it can be selected as the best model to predict the drying of PLB of length 10cm and diameter of 25mm since it gave good values of prediction.

Thus, the suitable drying method depends on the conditions under which the research is carried out. The establishment of the drying model appropriate for PLB may be useful during estimation of energy costs incurred when drying briquettes to a desired final MC through drying time prediction. The least accurate model across all weeks and drying methods, which was the Wang ve Sing is presented in Figure 4.7. A plot of experimental MR and Wang ve Sing model predicted MR against drying time from week 4 STD, 5 OSD, 6 STD and 5 STD respectively.

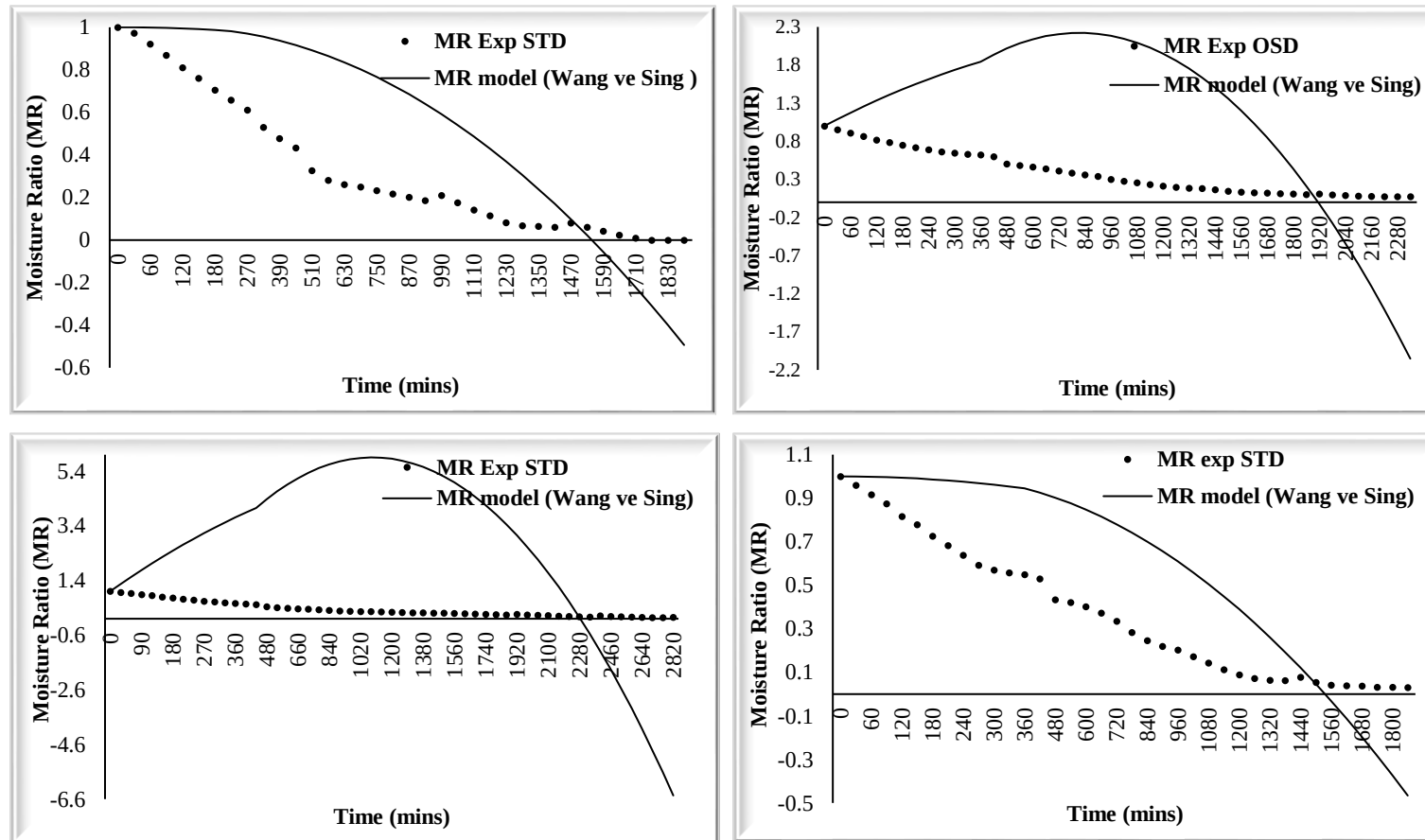


Figure 4.7 Variation of experimental MR and Wang ve Sing MR for week 4 STD, 5 OSD, 6 STD and 5 STD respectively against time

From Figure 4.7, it can be observed that the MR from the Wang ve Sing model does not compare very well with the experimental MR and thus it was selected as the least accurate model. Possible reasons are that the chosen time format (minutes) did not suit the calculation terms of the model. The model required time in hours (smaller numbers) not in minutes and this was realized after the experiments were carried out. Tables 4.3 and 4.4 show obtained drying model constants during the drying experiments of poultry litter briquettes.

Table 4.3 Obtained values of model constants for PLB under OSD

MODEL NAME	SUN DRYING																							
	WEEK 4								WEEK 5								WEEK 6							
	a	k	n	b	g	c	h	a	k	n	b	g	c	h	a	k	n	b	g	c	h			
Page	5.26E-03	8.20E-01						2.42E-03	9.06E-01						8.02E-03	7.07E-01								
Henderson and Pabis	9.27E-01	1.46E-03						9.59E-01	1.21E-03						8.63E-01	8.47E-04								
Logarithmic	2.25E+00	1.46E-03				4.12E-01		9.44E-01	1.30E-03				2.31E-02		8.21E-01	1.27E-03				1.03E-01				
Two term exponential	2.20E-01	5.76E-03						4.21E-01	2.18E-03						2.10E-01	3.88E-03								
MR model (Newton)		1.60E-03							1.28E-03							1.03E-03								
MR model (Wang ve Sing)	6.97E-08			-2.73E-07				3.00E-03			-1.84E-06				1.00E-02			-3.88E-06						
MR model (Modified Page)		4.90E-02	3.27E-02						1.19E-02	1.08E-01						5.86E-03	1.76E-01							
MR model (Midilli-kucuk)	9.92E-01	4.51E-03	8.40E-01	-2.76E-06				9.94E-01	2.45E-03	9.00E-01	-4.38E-06				1.03E+00	1.03E-02	6.72E-01	-3.88E-06						
MR model (Diffusion approximation)	2.76E-01	5.55E-03		2.13E-01				7.59E-02	1.19E-02		9.78E-02				3.93E-01	3.86E-03		1.55E-01						
MR model (Verma et al)	9.10E-01	1.43E-03			9.00E-01			9.51E-01	1.20E-03			2.44E-01			8.45E-01	8.23E-04			9.81E-01					
MR model (Modified Henderson and Pabis)	2.76E-01	5.64E-03		7.26E-01	1.18E-03	6.94E-04	1.20E+00	1.06E-01	1.64E-02		9.26E-01	1.17E-03	-3.17E-02	1.00E+00	3.90E-01	3.78E-03		6.05E-01	5.95E-04	4.94E-03	1.20E+00			
MR model (Two Term)	9.05E-02	k ₀ =2		9.10E-01		k ₁ =0.00143		4.92E-02	k ₀ =2		9.51E-01		k ₁ =0.0012		1.55E-01	k ₀ =2		8.45E-01		k ₁ =0.00082				

Table 4.4 Obtained values of model constants for PLB under STD

MODEL NAME	SOLAR DRYING																		
	WEEK 4							WEEK 5							WEEK 6				
	a	k	n	b	g	c	h	a	k	n	b	g	c	h	a	k	n	b	g
Page		3.46E-03	9.25E-01					1.40E-03	1.03E+00						5.10E-03	7.98E-01			
Henderson and Pabis	1.02E+00	1.97E-03						1.01E+00	1.74E-03						9.28E-01	1.19E-03			
Logarithmic	1.02E+00	1.94E-03				-4.82E-03		1.04E+00	1.54E-03				-4.63E-02		9.02E-01	1.66E-03			8.50E-02
Two term exponential	1.27E+00	2.05E-03						9.98E-01	1.72E-03						2.58E-01	3.85E-03			
MR model (Newton)		1.93E-03							1.72E-03							1.31E-03			
MR model (Wang ve Sing)	3.65E-06			-4.20E-07				6.97E-08			-4.24E-07				9.00E-03			-4.13E-06	
MR model (Modified Page)		1.13E-01	1.70E-02					1.25E-02	1.38E-01							7.67E-03	1.71E-01		
MR model (Midilli-kucuk)	1.03E+00	2.77E-03	9.43E-01	-1.16E-05				1.01E+00	2.37E-03	9.39E-01	-3.06E-05				1.06E+00	7.08E-03	7.60E-01	3.73E-06	
MR model (Diffusion approximation)	-2.58E-02	2.37E-01		8.36E-03				2.20E-01	1.72E-03		1.00E+00				4.93E-01	2.95E-03		2.43E-01	
MR model (Verma et al)	-2.58E-02	1.64E-01			1.98E-03			1.01E+00	1.74E-03			7.00E-01			9.14E-01	1.16E-03			9.81E-01
MR model (Modified Henderson and Pabis)	-5.24E-02	3.45E-01		8.61E-01	1.79E-03	1.89E-01	4.07E-03	3.53E-01	1.74E-03		6.56E-01	1.74E-03	-8.94E-03	1.20E+00	5.02E-01	3.73E-03		5.57E-01	7.55E-04
MR model (Two Term)	6.05E-01	$K_0=0.0022$		4.18E-01		$K_1=0.0017$		-8.96E-03	$K_0=4$		1.01E+00		$K_1=0.0017$		8.55E-02	$K_0=3$		9.14E-01	$K_1=0.0012$

The inbuilt solver in Microsoft office Excel was used to simulate the constants in tables 4.3 and 4.4 The constants were then fitted into each drying model in order to find the model which best describes the drying behavior of PLB.

4.5 Direct Combustion (DC) and Heat Distribution (H_D) of PLB

Results obtained during the process of DC are presented in Figures 4.8, 4.9 and 4.10. From each week age results from both DC of PLB from OSD and STD were paired for comparisons. H_D was measured at lengths 30cm, 60cm and 90cm from the brazier. The brazier surface temperature B_{ST} , was also recorded to observe how it correlates with H_D during DC. Raw data of the produced heat and its distribution is shown in Appendices E and F.

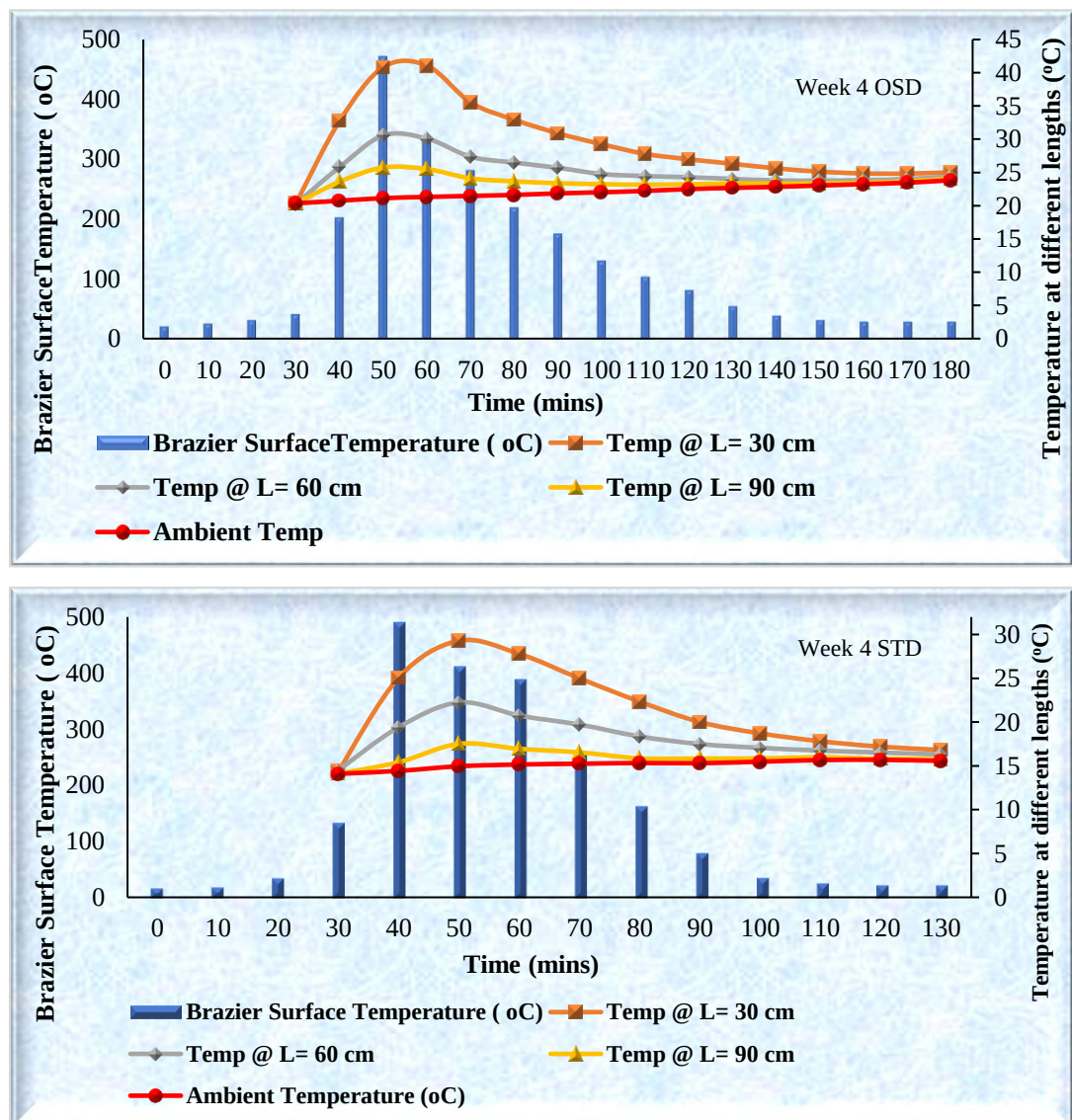


Figure 4.8 H_D during DC of PLB at week 4 from OSD and STD at different lengths.

From Figure 4.8, it can be observed that the H_D assumes the same behavior regardless of the drying method. B_{ST} is clearly seen to be constantly rising until the 60th minute where it started to drop. PLB for OSD produced a high temperature of 471°C at the 50th minute on the brazier surface which started dropping until the 140th minute. The B_{ST} had an initial temperature of 21.1°C resulting in a temperature rise of 449.9°C. As the combustion progressed, the temperature dropped to a constant temperature of 29°C almost close to the initial. Likewise, both temperatures at different lengths increased as B_{ST} increased. At a length of 30cm the highest temperature of 40.5°C was recorded which lasted for 10 minutes and started dropping.

The difference between the ambient temperature and the peak temperature at length 30cm was 19.34°C, thus heating the air at this point by this magnitude. A temperature drop of 4.95°C from the highest recorded temperature was experienced. The temperature continued to drop until the 180th minute to a temperature of 25°C. At a length of 60cm a highest temperature of 30.6°C was recorded and the air at this distance was heated to an increment of 9.5°C in relation to the ambient. The temperature difference at peak for length 30cm and 60cm was 9.8°C. Length of 90cm had a peak temperature of 25.8°C hence only yielding a temperature difference of 4.7°C. Both lengths experienced continual temperature drop until the 180th minute.

DC for PLB from STD had peak B_{ST} of 489°C. B_{ST} had an initial temperature of 17°C meaning increase in temperature was 472°C. The peak was recorded at the 50th minute and started to fall until the 120th minute where a temperature of 23°C was recorded. At length 30, a peak of 29.3°C was recorded and had a difference of 14.3°C in relation to the ambient. A constant, recurring temperature drop was recorded until the 130th minute to 16.8°C which was closer to the ambient. At length 60cm, peaks of 22.2°C were record and managing to heat the air at this length by 7.2°C. The difference between length of 30cm and 60cm was 7.1°C of which there was not much of a difference when compared to the difference obtained from OSD. At a length of 90cm, a peak of 17.5°C was recorded thus heating the surrounding air by 2.5°C which was not effective. The difference in peak temperatures of B_{ST} from OSD and STD was 18°C which was not too much considering the different experiment times at different ambient temperatures.

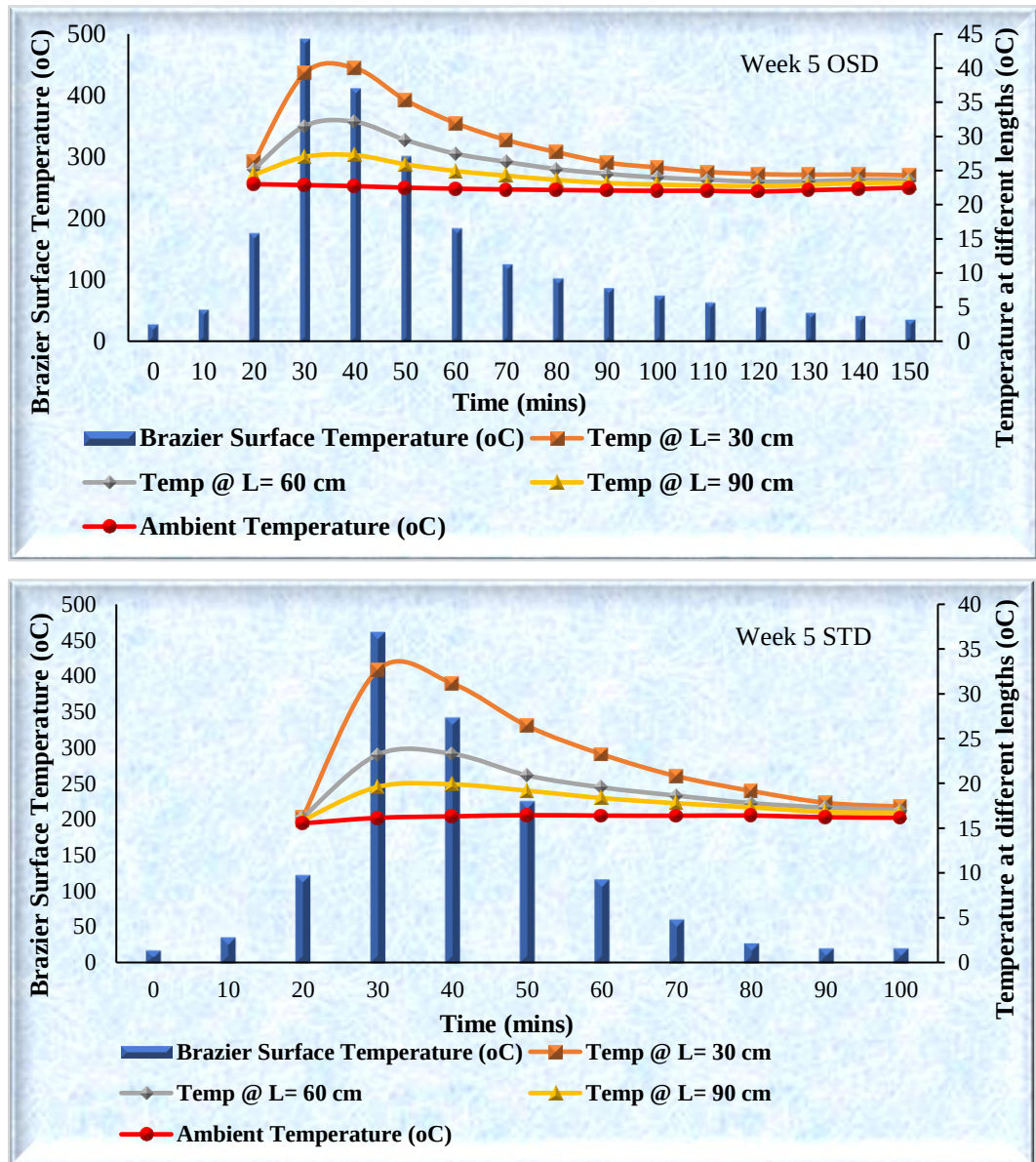


Figure 4.9 H_D during DC of PLB at week 5 from OSD and STD at different lengths.

Similarly, the temperature behavior of DC at week 5 trended as that at week 4 with B_{ST} clearly constantly rising until 30th minute where it started to drop. PLB for OSD produced high a temperature of 491°C at the 30th minute on the brazier surface which dropped until the 150th minute. The B_{ST} had an initial temperature of 23°C resulting in a temperature rise of 468°C.

B_{ST} dropped to a final temperature of 24.3°C at the 150th minute. A directly proportional relationship was depicted from the B_{ST} and different chosen lengths as they both increased and dropped similarly. 40°C was recorded at a length 30cm which lasted for 10 minutes and started dropping.

The difference between the ambient temperature and the peak temperature at a length of 30cm was 17°C thus heating the air at this point by this magnitude. A temperature drop of 4.69°C from the highest recorded temperature was experienced. Continual temperature drop occurred until the 150th minute. At a length of 60cm a topmost temperature of 32°C was recorded which also lasted for 10 minutes and the air at this distance was heated to an increment of 9°C in relation to the ambient. The temperature difference at peak for a length of 30cm and 60cm was 8°C. Length of 90cm had a higher temperature of 27.2°C hence only yielding a temperature difference of 4.2°C. Both lengths experienced continual temperature drop until the 150th minute. DC of PLB from OSD commenced from 1230hrs to 1500hrs.

B_{ST} of 461°C was recorded during the DC of PLB from STD as a peak temperature. B_{ST} had an initial temperature of 16°C meaning temperature increment was 445°C. The peak was also recorded at the 30th minute and started to fall until the 100th minute to 17°C. A highest temperature of 33°C was recorded and had a difference of 17°C in relation to the ambient at length 30cm. At a length of 60cm, peaks of 23°C were recorded and managing to heat the air at this length by 7°C. The difference between a length of 30cm and 60cm was 10°C which was higher compared to the difference obtained from OSD. At a length 90cm, a peak of 20°C was recorded thus heating the surrounding air by 4°C. DC of PLB from STD was started from 1010hrs to 1130hrs. The difference in peak temperatures of B_{ST} from OSD and STD was 30°C.

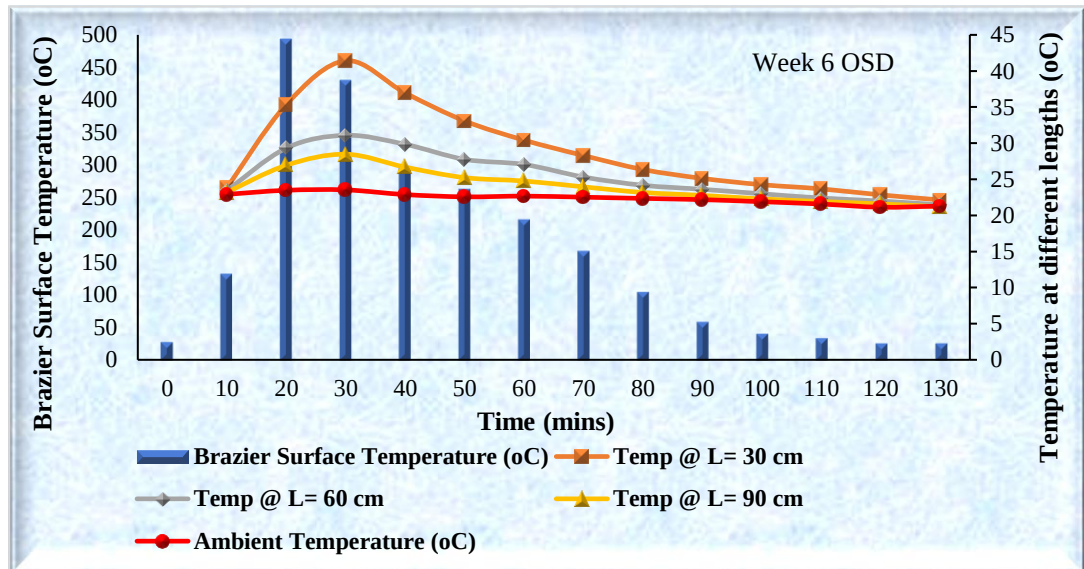
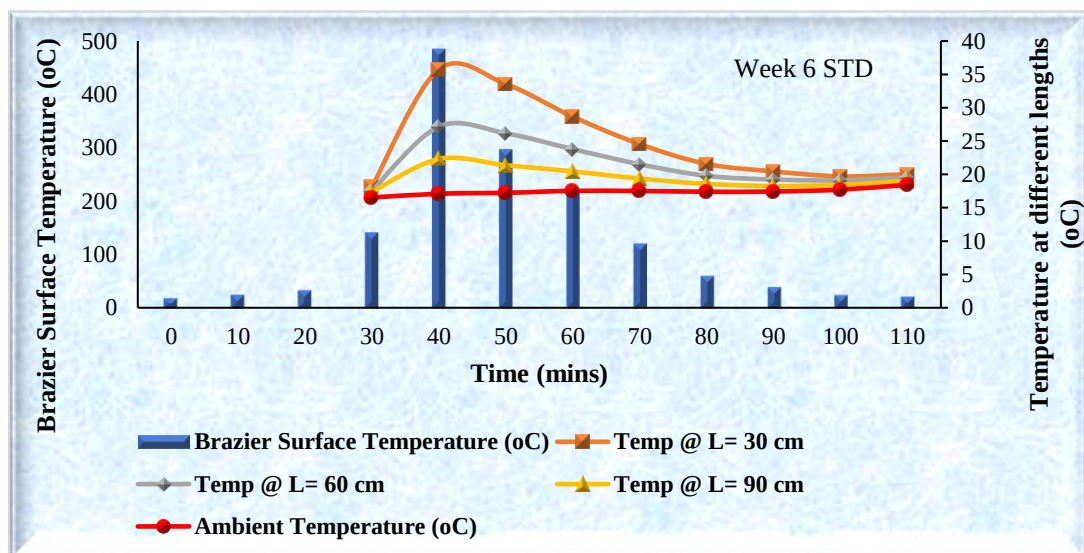


Figure 4.10 H_D during DC of PLB at week 6 from OSD and STD at different lengths.

PLB from OSD in week 6 had the highest B_{ST} of 493°C which was recorded at the 20th minute then dropped to 26°C at the 120th minute. The B_{ST} had an initial temperature of 28°C resulting in a temperature rise of 465°C. Equally, a directly proportional relationship was depicted from the B_{ST} and different chosen lengths as they both increased and dropped similarly. A peak temperature of 41.4°C was recorded at a length of 30cm.

The ambient temperature was 23.5°C and had a difference of 17.9°C when related with the peak temperature at a length of 30cm meaning that the air at this point was heated to that degree.

A temperature drop of 4.4°C from the highest recorded temperature was experienced. Continual temperature drop occurred until the 130th minute. At a length of 60cm the uppermost temperature of 31°C was recorded and the air at this distance was heated to an increment of 7.5°C in relation to the ambient. The temperature difference at peak for a length of 30cm and 60cm was 10.4°C. A length of 90cm had a higher temperature of 28.5°C hence only yielding a temperature difference of 5°C with the ambient air. Both lengths experienced continual temperature drop until the 130th minute. DC of PLB from OSD commenced from 1515hrs to 1740hrs.

B_{ST} of 485°C was recorded during the DC of PLB from STD as a peak temperature. B_{ST} had an initial of 19°C meaning generated heat was 466°C. The peak was recorded at the 40th minute and started to fall until the 110th minute to 22°C. A highest temperature of 35.8°C was recorded and had a difference of 18.7°C in relation to the ambient at a length of 30cm. At a length of 60cm, a peak of 27.2°C was recorded and managing to heat the air at this length by 10.1°C. The difference between a length of 30cm and 60cm was 8.6°C. At a length of 90cm, a peak of 22.3°C was recorded thus heating the surrounding air by 5.2°C. DC of PLB from STD was started from 1137hrs to 1326hrs.

As observed from the Figures 4.8, 4.9 and 4.10, B_{ST} was rapidly falling but the temperature drop at different lengths was not as rapid because the surrounding air was still warm. This resulted in a less rapid temperature drop. Despite of different times of experiment commencement, the temperature difference at different lengths in relation to the ambient were more or less the same across all weeks. From week 4 during the combustion of PLB from OSD which started at 0933hrs to 1233hrs, a highest temperature of 40.5°C was recorded at a length of 30cm at an ambient temperature of 21.1°C. The difference between these temperatures was 19.4°C. Similarly, DC at week 6 for PLB from OSD which started at 1515hrs to 1740hrs had a highest temperature of 41.4°C at a length of 30cm at an ambient of 23.5°C. The difference yielded between these temperatures was 17.9°C which was separated by only 1.5°C as compared to that from week 4. The averages of B_{ST} from week 4, 5 and 6 respectively were 480°C, 476°C and 489°C which were not that far apart indicating that they were more or less the same.

4.6 H_D of DC of Charcoal

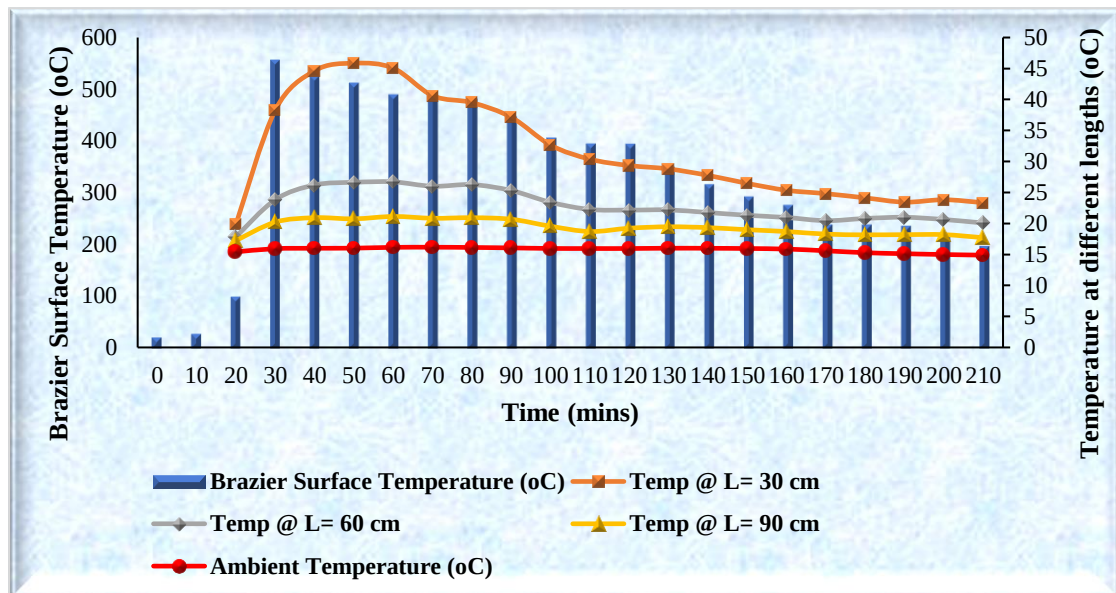


Figure 4.11 H_D during DC of Charcoal at different lengths

Figure 4.11 reveals the H_D during the combustion of charcoal at lengths of 30cm, 60cm and 90cm. B_{ST} is also plotted which represents the heat produced from the combustion of charcoal. Initially, B_{ST} had a temperature of 21°C which rose rapidly to highs of 555°C at the 30th minute. A temperature rise of 534°C was experienced on the surface of the brazier. The temperature then dropped constantly to 198°C at the 210th minute. At a length of 30cm, a peak temperature reading of 45.9°C was recorded which seemed to be constant for 10 minutes then dropped. The ambient temperature was 16.2°C making the air temperature at a length of 30cm to rise to 29.7°C. At 40 minutes, a length of 60cm had a high temperature reading of 26.6°C which remained constant for 40 minutes then started dropping.

The temperature difference between a length of 30cm and 60cm was 19.3°C. A length of 90cm had peak temperature readings of 20.9°C which also remained constant for 40 minutes. A length of 30cm did not maintain its peak temperatures for long because it was closer to the brazier thus it was sensitive to any temperature change. The DC of charcoal started from 1800hrs to 2130hrs. Charcoal had the highest temperatures during DC as compared to temperatures recorded from DC of PLB across all weeks. The temperature rise at a length of 30cm recorded during the DC of charcoal, which was 29.7°C, was higher than those recorded during DC of PLB which had an average of 17.4°C.

4.7 Comparison of B_{ST} of DC of PLB From OSD and STD to Charcoal

The plot of the temperature of the brazier surface measured from the combustion of PLB from all weeks from OSD and STD and charcoal is shown in Figure 4.12 to show their comparison.

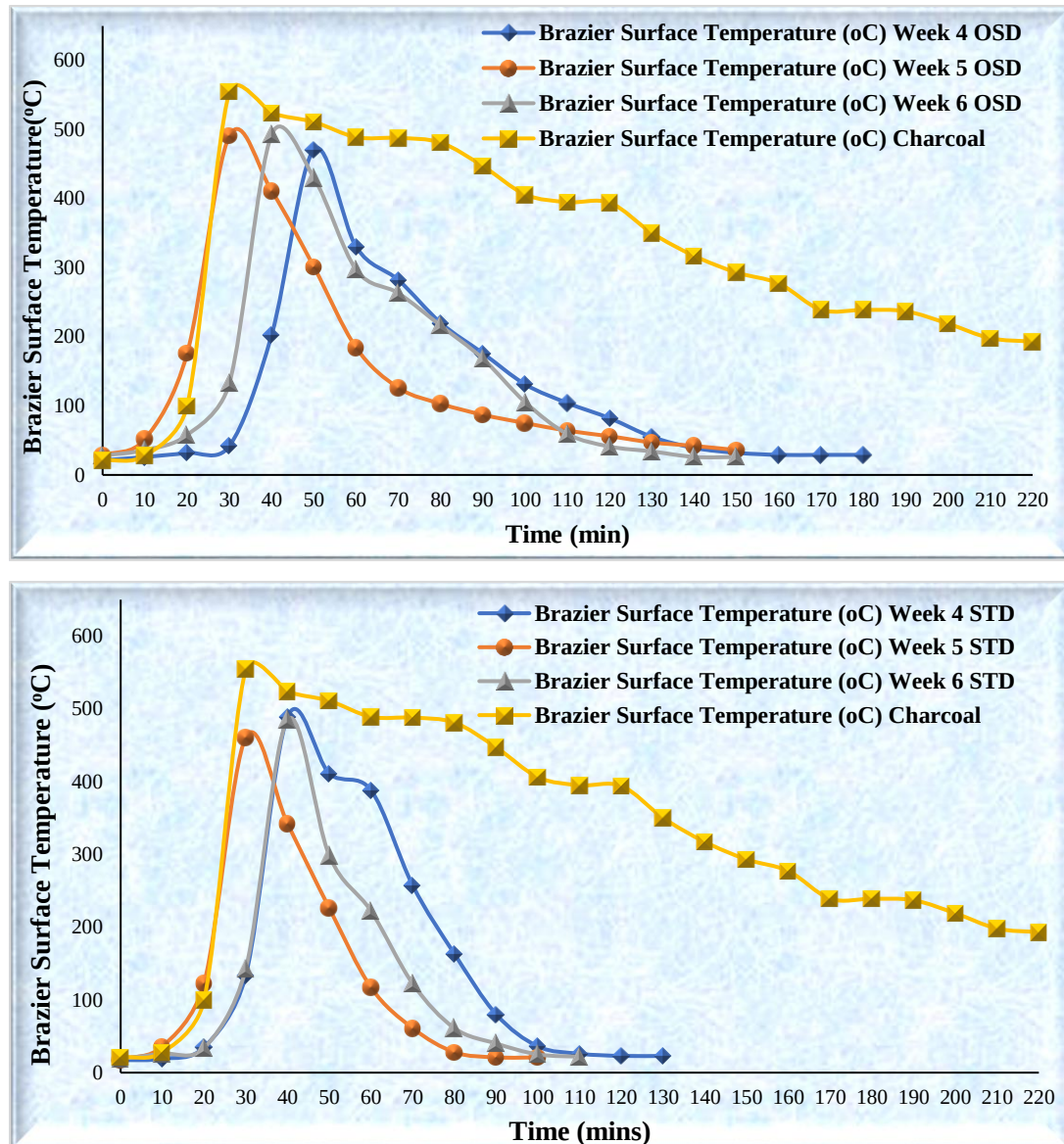


Figure 4.12 Comparing B_{ST} from DC of PLB from OSD and STD to Charcoal

From Figure 4.11 it can be clearly seen that charcoal burns longer than all PLB from all weeks. Charcoal was able to sustain high temperatures for at most 80 minutes. A peak of 555°C was recorded on the surface of the brazier at 30 minutes which then slightly dropped to 524°C thus a temperature drop of 31°C. The temperature further dropped and recorded a temperature of 406°C at the 100th minute. Charcoal is a

carbonized material with significant amounts of fixed carbon thus making it burn longer than PLB across all weeks. The remnant carbon in the material after volatile materials are driven off is known as fixed carbon, of which that belongs to charcoal ranges from 50% to 95% (Raju *et al.*, 2014). This was an influence as to how charcoal was able to burn for longer than PLB and even produce higher temperatures not only on the B_{ST} but at different lengths from the brazier. Additionally, the combustibility of charcoal was immensely influenced by the carbon and hydrogen content.

According to Falemara *et al.*, (2018), a low ash content images a high CV indicating that a material does not contain non-combustible matters. It was further reported that the combustion remnant is increased by ash content thus causing a decrease in the heating effect. In Figure 4.13 charcoal had the lowest ash content of 8.4%. Since it had a lower ash content, this may have been one other reason why it produced more heat than PLB. As seen from Figure 4.13 PL has more ash content than charcoal thus the length of combustion was reduced leading to less heat being produced. Charcoal stood the test of time because even after the burn out of PLB at about 130 minutes, higher temperatures of 350°C were still being recorded. In average, PLB was able to produce suitable temperatures at lengths of 30cm and 60cm for 90-100 minutes while charcoal had the longest suitable heat distribution of 140-180 minutes.

4.8 Statistical Analysis B_{ST} of Charcoal and PLB

The seven treatments (six being of PLB at different weeks and different drying method) were tested to determine the variation between their means. The usefulness of this determination was to verify if there is any contrast between the temperatures produced from the seven treatments. Tests were done at a significance level of 0.05. The results are presented in Table 4.5 and Table 4.6.

Table 4.5 Summary of analysis of variance Single Factor (B_{ST} of charcoal and PLB)

B_{ST} of charcoal and PLB (°C)	Count	Sum	Average	Variance
Week 4 STD	14	2101	150.0714	28089.61
Week 5 STD	11	1454	132.1818	22419.36
Week 6 STD	12	1497	124.7500	20956.20
Week 4 OSD	19	2333	122.7947	16170.04
Week 5 OSD	16	2279	142.4375	19765.86
Week 6 OSD	16	2413	150.8125	22541.63
Charcoal	23	7401	321.7826	24470.81

Table 4.6 Analysis of variance Single Factor between (B_{ST} of charcoal and PLB)

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between B _{ST} of charcoal and PLB	632788.9	6	105464.8	4.802	0.000231	2.187
Within B _{ST} of charcoal and PLB	2283907.9	104	21960.65			
Total	2916696.8	110				

Microsoft Excel inbuilt Analysis of Variance (ANOVA) single factor was used to compute the level of variation between the means of the seven treatments. From Table 4.5 it can be seen that there is little variation between means of heat produced of week 4 OSD and week 4 STD, week 5 OSD and week 4 STD since the means are several thousands apart. Table 4.5 also shows that mean values of the remaining treatment means are more or less the same thus showing less variation. Less variation means that the tested parameter, being the brazier surface temperature, is the same for the compared means. Since variation was observed from Table 4.5, Table 4.6 was used to find out where the variation existed. Therefore, the variation between the seven treatments was carried out. The Mean Square (MS) for treatments was found to be 105464.8 while that for the error was found to be 21960.65.

The aforementioned parameters were used to calculate the F value which aids, by comparing it to F critical, to tell if there is a significant difference between the treatment means. As seen from Table 4.6, the calculated F is greater than F critical indicating that there is variation between treatment means also meaning that there is variation between the brazier surface temperatures. Also, the P-value was calculated to be 0.000231 being less than the significance level of 0.05, which arrives to the previous mentioned conclusion. Thus, this led to the conclusion that there is a significant difference between the treatment means at a significance level of 0.05 (95%) with a probability of 0.000231 (0.0231%) for the treatment means to be similar.

4.9 Multiple Comparisons in Least Significant Difference (LSD)

Since ANOVA could not identify where the variation was from the tested treatment means, Statistical Package for Social Sciences (SPSS) was used to determine where this difference lied. LSD under multiple comparisons was used to carry out this test. The test was also carried out at the significance level of 0.05. The results are presented in Table 4.7.

Table 4.7 LSD Multiple Comparisons B_{ST} of charcoal and PLB OSD and STD

(I) B _{ST}	(J) B _{ST}	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
B _{ST} Charcoal	B _{ST} W4 OSD	198.98787	45.94165	0.00003	107.88386	290.09188
	B _{ST} W4 STD	171.71118	50.23374	0.00090	72.09578	271.32658
	B _{ST} W5 OSD	179.34511	48.24263	0.00033	83.67815	275.01206
	B _{ST} W5 STD	189.60079	54.32526	0.00071	81.87176	297.32982
	B _{ST} W6 OSD	170.97011	48.24263	0.00059	75.30315	266.63706
	B _{ST} W6 STD	197.03261	52.77182	0.00031	92.38410	301.68112
B _{ST} W4 OSD	B _{ST} Charcoal	-198.98787	45.94165	0.00003	-290.09188	-107.88386
	B _{ST} W4 STD	-27.27669	52.19619	0.60238	-130.78369	76.23031
	B _{ST} W5 OSD	-19.64276	50.28285	0.69686	-119.35553	80.07001
	B _{ST} W5 STD	-9.38708	56.14487	0.86754	-120.72447	101.95031
	B _{ST} W6 OSD	-28.01776	50.28285	0.57859	-127.73053	71.69501
	B _{ST} W6 STD	-1.95526	54.64319	0.97152	-110.31476	106.40423
B _{ST} W4 STD	B _{ST} Charcoal	-171.71118	50.23374	0.00090	-271.32658	-72.09578
	B _{ST} W4 OSD	27.27669	52.19619	0.60238	-76.23031	130.78369
	B _{ST} W5 OSD	7.63393	54.23245	0.88833	-99.91106	115.17892
	B _{ST} W5 STD	17.88961	59.70796	0.76507	-100.51352	136.29275
	B _{ST} W6 OSD	-0.74107	54.23245	0.98912	-108.28606	106.80392
	B _{ST} W6 STD	25.32143	58.29813	0.66494	-90.28596	140.92882
B _{ST} W5 OSD	B _{ST} Charcoal	-179.34511	48.24263	0.00033	-275.01206	-83.67815
	B _{ST} W4 OSD	19.64276	50.28285	0.69686	-80.07001	119.35553
	B _{ST} W4 STD	-7.63393	54.23245	0.88833	-115.17892	99.91106
	B _{ST} W5 STD	10.25568	58.04278	0.86009	-104.84532	125.35668
	B _{ST} W6 OSD	-8.37500	52.39353	0.87331	-112.27333	95.52333
	B _{ST} W6 STD	17.68750	56.59148	0.75525	-94.53552	129.91052
B _{ST} W5 STD	B _{ST} Charcoal	-189.60079	54.32526	0.00071	-297.32982	-81.87176
	B _{ST} W4 OSD	9.38708	56.14487	0.86754	-101.95031	120.72447
	B _{ST} W4 STD	-17.88961	59.70796	0.76507	-136.29275	100.51352
	B _{ST} W5 OSD	-10.25568	58.04278	0.86009	-125.35668	104.84532
	B _{ST} W6 OSD	-18.63068	58.04278	0.74887	-133.73168	96.47032
	B _{ST} W6 STD	7.43182	61.85853	0.90460	-115.23596	130.09960
B _{ST} W6 OSD	B _{ST} Charcoal	-170.97011	48.24263	0.00059	-266.63706	-75.30315
	B _{ST} W4 OSD	28.01776	50.28285	0.57859	-71.69501	127.73053
	B _{ST} W4 STD	0.74107	54.23245	0.98912	-106.80392	108.28606
	B _{ST} W5 OSD	8.37500	52.39353	0.87331	-95.52333	112.27333
	B _{ST} W5 STD	18.63068	58.04278	0.74887	-96.47032	133.73168
	B _{ST} W6 STD	26.06250	56.59148	0.64609	-86.16052	138.28552
B _{ST} W6 STD	B _{ST} Charcoal	-197.03261	52.77182	0.00031	-301.68112	-92.38410
	B _{ST} W4 OSD	1.95526	54.64319	0.97152	-106.40423	110.31476
	B _{ST} W4 STD	-25.32143	58.29813	0.66494	-140.92882	90.28596
	B _{ST} W5 OSD	-17.68750	56.59148	0.75525	-129.91052	94.53552
	B _{ST} W5 STD	-7.43182	61.85853	0.90460	-130.09960	115.23596
	B _{ST} W6 OSD	-26.06250	56.59148	0.64609	-138.28552	86.16052

Based on observed means. The error term is Mean Square (Error) = 21960.653

*. The mean difference is significant at the 0.05 level

B_{ST} = Brazier Surface Temperature

From the results in Table 4.7 the nature of variation is clearly seen. Comparisons start by comparing B_{ST} of charcoal to the other treatments. The obtained values for the probability of this comparison being similar were 0.00003, 0.00090, 0.00033, 0.00071, 0.00059 and 0.00031 belonging to B_{ST} week 4 OSD, B_{ST} week 4 STD, B_{ST} week 5 OSD, B_{ST} week 5 STD, B_{ST} week 6 OSD and B_{ST} week 6 STD respectively. The values attained are less than the significance level of 0.05 meaning that there is a significant difference between temperatures from the combustion of charcoal as compared to those from the temperatures of the combustion of PLB at all weeks from either method of drying. This means that charcoal produces more heat than PLB regardless of the PL age as can be seen from Figure 4.12. The subsequent comparison was that of week 4 OSD to all other treatments.

Temperatures acquired at this age were compared to those of charcoal and the variance of these two means had a probability of 0.00003 of being the same which is close to nothing, meaning that it is significant and that more temperatures can be obtained from charcoal than PLB at week 4 OSD. The next P-values were 0.60238, 0.69686, 0.86754, 0.57859, 0.97152 for B_{ST} week 4 STD, B_{ST} week 5 OSD, B_{ST} week 5 STD, B_{ST} week 6 OSD and B_{ST} week 6 STD respectively. These values are all greater than the significance level of 0.05 meaning that there is no significant difference between the temperatures produced by PLB at week 4 OSD and other PLB from the remaining weeks from either method of drying.

The remaining weeks were also compared to charcoal and the obtained P-value for all of them was less than the significance level of 0.05 which gave a manifestation that there is a high significant difference between the temperatures produced from charcoal and all PLB at all ages from either method of drying. This means that charcoal produces more heat than PLB as revealed in Figures 4.12 where charcoal produced a maximum of 555°C whereas PLB produced an average of 482°C. Correspondingly, PLB from all the remaining weeks and drying method were compared amongst each other and gave the lowest P-value of 0.57859 and the highest of 0.98912 giving a revelation that there is a 58% - 99% chance that the heat acquired from PLB at any age and drying method can be the same. Therefore, the conclusion is that there is no significant difference between PLB B_{ST} at any age and drying method at a significance level of 0.05%. This is true because they produced heat in a range of 461°C to 493°C which are not that far apart.

4.10 Ash Content

Important information regarding PL quality is provided by the ash content since it measures the mineral content of the litter. The comparisons of ash content at different ages of PLB according to weeks is shown in Figure 4.13.

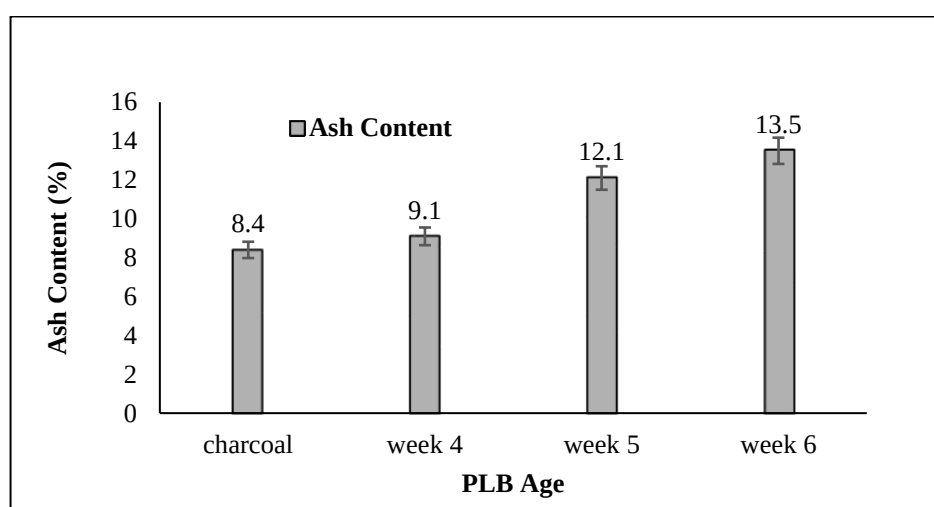


Figure 4.13 Ash content in percentage of the charcoal and PLB at different weeks

It is apparent that as PL ages, according to weeks, the amount of ash produced increases. Knowing the ash content provides information of the extent of clogging and burning of a substance. The burning rate and heating value of a fuel are diminished by a high ash content. PLB at week 4 as seen in Figure 4.13 had the lowest ash content of 9.1% followed by week 5 with 12.1% and week 6 being the highest with ash content of 13.5%. Babatope *et al.*, (2012) carried out a research on Proximate Composition and Post-Production Stability of Poultry Waste Fertilizer Pellets and obtained results which showed that broiler litter pellets contained more ash than layer litter. Broiler litter had an ash content of 13.27 and 14.17% while layers had lesser at 12.65 and 13.60%.

Acharya *et al.*, (2014) also carried out a research on Ash Analysis of Poultry Litter, Willow and Oats for Combustion in Boilers and found the ash content to be 11.5%. The broiler litter obtained in this study had the ash content within this range. Since there was more of the wood shaving than organic matter (poultry manure) at week 4, less ashes were produced because of little organic matter to burn. The quantity of manure in the litter increases with the growth of chickens and when the litter is

combusted more ashes will be produced since there will be more organic matter to burn and less of the wood shavings. In line with this, Rico-contreras *et al.*, (2017), reported that ash content depends on the organic matter contained in poultry litter available for combustion. Also, Babatope *et al.*,(2012) pinpointed that poultry litter normally has high ash content because of the amount of dirt contamination which has occurred in the litter. Additions were that ash content will be high in old litter since significant dirt would have mixed into the litter.

And in this regard, Acharya *et al.*, (2014) pointed out that regular disposal of ash is required because the thick deposit of the ash prevents heat flow when poultry litter is combusted. Ash accumulation will reduce the burner efficiency thus less heat will be produced. Charcoal was used as a control and it had a low ash content of 8.4% which was almost similar to that obtained at week 4. The ash content of charcoal was around the value found by Koyuncu and Pinar, (2007) which was 5.86%.

4.11 The Calorific Value (CV) Determination of PLB

Two samples of PLB at week 4 OSD and week 6 STD were used to represent all other PLB for CV experiments since they were a week apart. For charcoal, CV from literature was used for this comparison. The CV obtained from the experiment are shown in table 4.8 and also in Appendix G.

Table 4.8 Comparison of CV from charcoal and PLB from W4 OSD and W6 STD

Biomass	Calorific Value (CV-MJ/kg)
PLB Week 4 OSD	15.65
PLB Week 6 STD	14.57
Charcoal	30.8

Table 4.8 Shows that there is more or less of a similarity between CV from week 4 and week 6. Week 4 had a gross CV of 15.65MJ/kg while at week 6 the CV was 14.57MJ/kg. As seen from Table 4.7 the P-value of week 4 OSD and week 6 STD was 0.97152 meaning that there is a 97% chance of similarity between the heat produced during the combustion of PLB from these weeks. So, the case is as seen from Table 4.8 where there is not much of a difference between the CV obtained from the CV

experiments. Equally, the B_{ST} which were measured from week 4 OSD and week 6 STD were 471°C and 485°C respectively, indicating the less difference between the two weeks. The slight drop of CV at week 6 STD may have been due to the decomposition of essential elements needed to enhance combustion. These essential elements are namely Nitrogen, Carbon and Hydrogen. Also, since the ash content was increasing with number of weeks, this might have led to a minor diminish in the CV obtained at week 6 since more ash reduces the heating value of a material.

The CV of PLB obtained from this study is also in line with the one acquired by (Abelha *et al.*, 2003) under a research titled combustion of poultry litter in a fluidized bed combustor. PL from their study had the highest CV of 13.5 MJ/kg which was said to be about half of coal. The difference of the CV from literature and those calculated is slightly different, but in a comparable region. A CV of 30.8 MJ/kg was obtained from (Sánchez, Pasache and García, 2014) which was chosen to represent charcoal CV in this study. Both CV of PLB of the samples tested were lower than that of charcoal. They were about half the CV for charcoal which stands at 49.1%. Charcoal has high carbon and hydrogen content compared to PLB since it has been thermally treated by pyrolysis. According to Raju *et al.*, (2014), an increase in carbon and hydrogen content results to an increase in CV. Also, the fixed carbon of charcoal was reported to range from 50% to 90%. Hence charcoal produces more heat than PLB as seen from the CV.

4.12 Closing Remarks

This chapter has accounted in detail the average climatic conditions encountered at the period of the experiments, the direct combustion, heat distribution, ash content as well as calorific value experiments and the results obtained. The results of the study with regards to the specific objectives have also been extensively discussed in this chapter. The next chapter highlights the conclusions and recommendations drawn from this study.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

This chapter presents the conclusions and recommendations drawn from the study.

5.1 Conclusions

The following can be made from this work:

1. The Logarithmic drying model is the best model for predicting the drying behaviour of PLB from both STD and OSD since it proved to be the most consistent model with values of prediction criterion; R^2 of 9.93E-01-9.99E-01; χ^2 of 1.36E-11-6.50E-14; and RMSE of 2.94E-02-1.30E-02.
2. PLB has lower volatiles, fixed carbon, higher nitrogen and ash content than charcoal thus less heat was produced from PLB as compared to charcoal. PLB from all weeks was not able to sustain high temperatures for long. It generally produced sufficient heat for a maximum of 100 minutes compared to charcoal which was able to burn for a maximum of 180 minutes.
3. A gray smoke was observed when firing up briquettes and this persisted for 20 minutes before the experiment started. The smoke cleared out until the time approached 30 minutes after the firing up. More smoke seemed to be experienced during the firing up of PLB at week 4. This effect is due to higher content of gluten and protein in the cassava flour.
4. Generally, as seen from the CV obtained and heat produced from PLB, the age of PL does not affect the CV or heat produced by the PLB, thus PL at any age can be used for making briquettes. But using PL at an early age (week 4) will require more binder which will be costlier as compared to the binder requirement at week 6. Also, using PL at week 4 will contribute to costs of replacing the bedding material, so it is best to get PL at final clearance.
5. A distance of 30cm from the brazier showed a positive response on heat distribution since temperatures were sustained on the range of 22°C to 32°C (suitable for chicks), thus it can be an effective distance to provide comfort to chicks during cold weather. The distance of 60 cm was as well effective unlike that of 90cm which gave low air temperatures.
6. The results obtained from the PLB dried from STD and OSD showed no difference in terms of CV, heat distribution and the BST since they were all dried to the same final mass. Despite this, OSD took longer than STD thus choosing this way of drying will result in longer drying periods.

7. Ash content of PLB increased as the weeks lapsed and this causes concern of the disposal of the ash as well as affecting the CV of the briquettes by reducing it. In spite of this, acquiring PL at week 4 contributes to costs incurred since the bedding will have to be replaced, hence it is better to get the final product which is regarded to as a waste.

5.2 Recommendations

The following recommendations were drawn from this study:

1. The equipment which was used for making PLB was a hand grinder with a low compression pressure which may as well have led to weaker briquettes. Stronger briquettes tend to burn longer and produce more heat, therefore, a briquette making machine which can induce more pressure can be utilized in making briquettes. Briquetting pressure is important because under pressure, materials will squeeze around to envelope particles and facilitate inter-particle bonding.
2. In this research only one diameter (25mm) was used therefore bigger sizes could be tried wherein the length of burning, heat produced and consequently the extent of heat distribution can be observed. Also, a hole can be created in the center of briquettes for uniform combustion and smoke reduction.
3. In order to strengthen the briquettes, hot water may be used instead of cold water so that a denser material can be obtained as a final product when densifying. Lignin in biomass, in this case PL, can be melted by high temperatures thus causing the PL to bind naturally under pressure. Less or no starch may be required when this is implemented. With increasing temperature pressure required for briquetting goes down.
4. The briquettes from this study were hand crushed and mixed with a binder and this may have resulted in weaker bonding of the briquettes thus leading to shorter combustion period. In this fashion, a suitable machine can be used to grind PL to powder form before mixing it with a binder. This may constitute more stable briquettes during combustion thus leading to more heat production. Particle size plays a vital role on the durability of a briquette, that is, more durable briquettes are made from finer particles because they are able to self-adhere forming strong intermolecular bonds.

5. As observed from Figure 4.12 after 60 minutes a peak temperature was reached and consequently it started dropping. So, at this point of time, more briquettes can be added to the brazier so that high temperatures are maintained for longer periods.
6. The briquettes can also be charred so that the amount of volatile matter and carbon content are increased hence increasing the heat output of PLB.
7. The resulting ash from combustion is rich in macro elements like Potassium and Phosphorus and can be used as a fertilizer. So, for fertilizer recommendation purposes, experiments can be carried out as to determine the level at which the ash should be applied to the receiving crop.
8. Biomass briquettes are environmentally friendly and are globally embraced as a potential energy substitute for fossil fuels and charcoal. The utilization of these briquettes can help to mitigate concerns over; deforestation and its outcomes, agricultural and wood wastes management issues as well as contamination problems. Enhancements on job opportunities, market diversification and rural economic empowerment can also be accomplished.

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APPENDIX A: PICTURES OF VARIOUS INSTRUMENTATION USED



1=Charcoal, 2=Temperature probe, 3=Parts of a hand grinder (mincer mincer), 4=Cassava meal, 5=Measuring jug, ruler and spoon, 6=Nozzle and 7=Digital multimeter with Type k Temperature probe.

APPENDIX B: THE FLOUR-FEED RATIO AT DIFFERENT WEEKS WHEN MAKING PL PASTE

Week	Feed (g)	Flour (g)	Percentage (%)
4	3600	1600	44.4
5	3600	600	16.7
6	3600	500	13.9

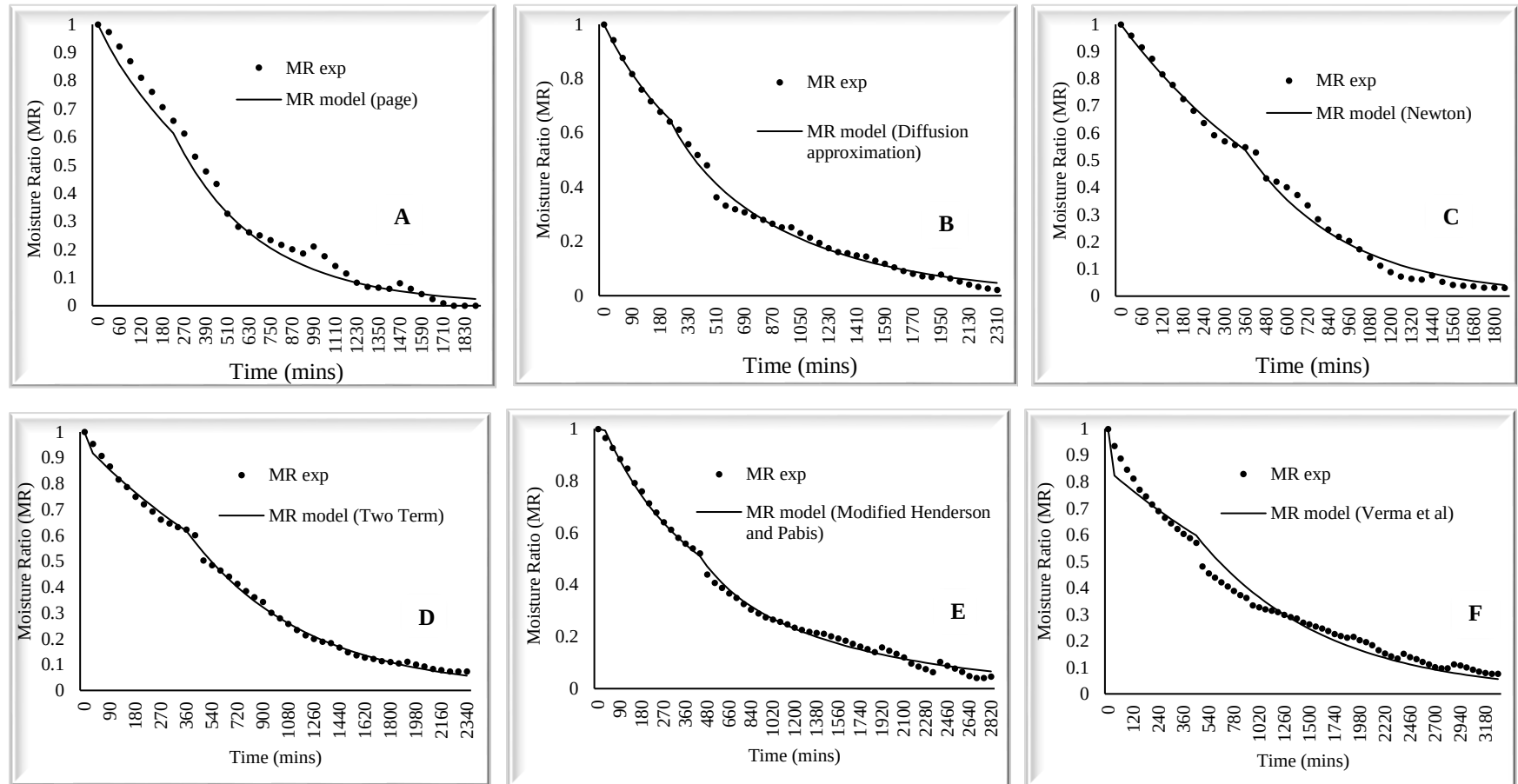
APPENDIX Bii: CLIMATIC CONDITIONS ON A TYPICAL DRYING DAY

Time (mins)	T _{CU} (°C)	T _{DU} (°C)	T _{CH} (°C)	T _{AM} (°C)	Solar insolation (W/m ²)
0	25.11	26.48	22.89	18.25	444
30	36.68	39.41	29.54	19.61	582
60	43.95	41.52	27.68	20.78	558
90	47.9	44.24	29.55	22.11	661
120	50.42	46.01	30.59	23.33	713
150	54.67	50.24	35.6	24.64	746
180	58.56	53.33	41.17	25.92	767
210	60.15	55.25	40.7	26.95	765
240	56.62	50.35	38.49	26.85	755
270	55.86	51.87	40.62	27.2	790
300	44.38	38.01	29.64	26.31	168
330	30.03	28.54	25.78	24.24	90
360	26.74	25.86	23.78	22.89	96
390	33.86	29.3	25.86	24.58	163
420	36.04	30.88	27.5	26.18	101

APPENDIX C: MOISTURE LOSS OF PLB FROM ALL WEEKS AGAINST TIME

Time (mins)	MC _{wb}					
	Week 4 Sun	Week 5 Sun	Week 6 Sun	Week 4 Solar	Week 5 Solar	Week 6 Solar
0	59.2	60.4	62.3	59.2	60.4	62.3
30	57.8	59.3	60.7	58.5	59.4	61.5
60	56.0	58.1	59.5	57.2	58.3	60.5
90	54.3	56.9	58.3	55.8	57.1	59.4
120	52.4	55.5	57.3	54.1	55.5	58.3
150	51.0	54.6	56.0	52.5	54.3	56.7
180	49.6	53.3	55.2	50.6	52.5	55.7
210	48.2	52.3	54.2	48.9	51.0	54.1
240	47.1	51.4	53.3	47.0	49.3	52.9
270	44.8	50.2	52.4	43.5	47.5	51.4
300	43.0	49.6	51.6	40.9	46.5	50.3
330	41.1	49.1	50.7	38.6	45.9	49.0
360	34.5	48.7	49.9	32.2	45.6	48.0
390	32.6	47.8	49.3	29.0	44.7	47.2
420	31.6	43.4	48.5	27.5	39.8	46.3
480	30.9	42.5	44.3	26.6	39.1	42.1
540	29.9	41.4	42.9	25.3	37.9	40.3
600	28.9	40.2	42.1	24.0	36.2	39.1
660	27.9	38.6	41.1	22.6	33.8	37.8
720	26.8	37.0	40.2	21.3	30.2	36.6
780	26.8	35.5	39.2	23.4	27.2	35.0
840	25.1	34.3	38.2	20.4	25.1	33.5
900	23.7	31.4	37.5	17.0	23.6	32.4
960	22.0	29.9	35.6	14.3	20.8	31.3
1020	20.3	28.2	35.1	10.7	17.8	30.6
1080	19.0	26.3	34.6	9.0	14.7	29.9
1140	18.5	24.6	34.2	8.6	11.9	29.1
1200	17.7	23.3	33.8	8.1	9.9	28.0
1260	17.4	22.3	33.1	10.5	8.9	27.3
1320	15.9	21.8	32.4	8.1	8.6	26.7
1380	14.6	20.2	32.0	5.8	10.5	26.2
1440	13.2	18.4	30.8	3.4	7.6	25.9
1500	11.8	17.2	30.3	1.4	6.0	25.0
1560	10.5	16.3	29.6	0.2	5.5	24.2
1620	9.5	15.7	29.0	0.2	5.3	23.4
1680	9.1	14.8	28.2	0.2	4.5	22.3
1740	10.2	14.4	27.2		4.5	21.2
1800	8.5	13.7	26.5		4.4	20.1
1860	7.0	14.6	26.0			18.9
1920	5.6	13.3	26.3			20.9
1980	4.5	12.4	25.2			19.4
2040	3.8	11.3	24.5			18.2
2100	3.0	10.8	23.3			16.6
2160		10.1	21.5			13.8
2220		10.1	20.1			12.3
2280		10.1	19.0			11.1
2340			18.1			9.6
2400			20.0			14.6
2460			18.7			12.8
2520			17.9			11.4
2580			16.8			9.7
2640			15.6			7.5
2700			14.4			6.5
2760			13.9			6.5
2820			13.9			
2880			15.6			
2940			15.2			
3000			14.2			
3060			13.2			
3120			12.3			
3180			11.6			
3240			11.2			
3300			11.2			

APPENDIX D: SOME OF THE MODELS USED FOR THIN LAYER DRYING OF PLB FROM ALL WEEKS



A=Week 4 STD, B=Week 4 OSD, C=Week 5 STD, D=Week 5 OSD, E=Week 6 STD, and F=Week 6 OSD.

APPENDIX E: COMPARISON OF TEMPERATURE FROM DC OF PLB AND CHARCOAL

Time (mins)	Brazier Surface Temperature (°C) Week 4 STD	Brazier Surface Temperature (°C) Week 5 STD	Brazier Surface Temperature (°C) Week 6 STD	Brazier Surface Temperature (°C) Charcoal
0	17	18	19	21
10	19	36	26	28
20	35	123	34	100
30	134	461	143	555
40	489	342	485	524
50	411	226	298	511
60	388	117	222	489
70	257	61	122	488
80	163	28	61	481
90	80	21	40	447
100	36	21	25	406
110	26		22	395
120	23			394
130	23			350
140				317
150				293
160				277
170				239
180				239
190				237
200				219
210				198
220				193

APPENDIX F: DISTRIBUTION OF TEMPERATURE FROM THE DC OF PLB AT DIFFERENT LENGTHS FROM THE BRAZIER

Time (mins)	B _{ST} (°C)	Temp @ L= 30 cm (°C)	Temp @ L= 60 cm (°C)	Temp @ L= 90 cm (°C)	Ambient Temperature (°C)
0	28				
10	133	23.81	23.41	23.19	22.91
20	493	35.37	29.33	26.95	23.48
30	430	41.42	31.09	28.47	23.53
40	297	36.95	29.84	26.68	22.88
50	263	33.08	27.76	25.23	22.57
60	216	30.42	27.05	24.76	22.67
70	168	28.29	25.31	23.95	22.52
80	105	26.35	24.17	23.17	22.35
90	59	25.12	23.61	22.77	22.18
100	41	24.25	22.99	22.28	21.89
110	34	23.67	22.4	21.92	21.57
120	26	22.84	21.99	21.59	21.13
130	26	22.14	21.46	21.19	21.29

APPENDIX G: ZAMBIA BUREAU OF STANDARDS CALORIFIC VALUE DETERMINATION REPORT



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Attn: Jason Molefe Cell: 0964-349149
Company: UNZA (SCHOOL OF ENGINEERING)
Date Reported: 28.08.2018
Report No. 2018/08/TL 23590

Type of Samples: Poultry Litter Briquette
Date Submitted: 23.08.2018
Date Tested: 24-27.08.2018

LABORATORY TEST REPORT

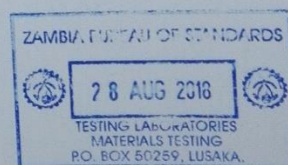
LABORATORY'S SAMPLE ID			TL 23590/1	TL 23590/2
CUSTOMER'S SAMPLE ID			-	-
SAMPLE DESCRIPTION			Poultry Litter Briquettes W4	Poultry Litter Briquettes W6
PARAMETER	UNITS	TEST METHOD	TEST RESULTS	TEST RESULTS
Gross calorific value	MJ/kg	ASTM D 5865	15.65	14.57

PREPARED BY: G MUSUKWA
DESIGNATION: LABORATORY ANALYST

SIGNATURE:

APPROVED BY: D PHIRI
DESIGNATION: SNR LABORATORY ANALYST

SIGNATURE:



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