

EVALUATING THE EFFICACY OF A HYBRID SOLAR-THERMOPHILIC HEAT
COLLECTOR FOR FOOD DRYING APPLICATION

BY

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of Master of Science in Energy Studies (Renewable Energy Resources), Department of
Energy Engineering of Moi University, Eldoret, Kenya.

2020

DECLARATION

DECLARATION BY THE STUDENT

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DEDICATION

Here I devote my daughters Chibubi Mwape and Luyando Mwape to this dissertation. Thank you for supporting me and helping me pray at all times. If it were not for your devotion, motivation, support and dedication, I would never have made it this far, I thank you and love you with all my heart.

ABSTRACT

Many farmers in Africa and in most of the developing nations depend on natural sun drying to preserve perishable products since it is cheap source of energy ,simple to use and renewable. However, the sun is not always available especially during the rainy season & at night. Open air-drying is unhygienic as it exposes foods to soil/dust, foreign matter, rain & other airborne contaminants that increase the danger of biodegradation and shorten shelf life. Delayed and insufficient dehydration contributes significantly to the accumulation of harmful mycotoxins/aflatoxins in stored produce. The main objective of this study was to evaluate the efficacy of a hybrid solar thermophilic heat collector for food drying applications. Specifically, it was sought firstly to characterize the suitability of locally available farm wastes for hot composting and secondly to quantify the energy and food drying potentials of a prototype solar thermophilic dryer that has been developed for use on small farms. The study was conducted on a farm in Kitale, Trans-Nzoia County from April 2019 to July 2019. Green grass clippings and weeds, cow and chicken manure, shredded maize stover and sawdust were sampled locally and analysed at Kenya Agricultural and Livestock Research Organization (KALRO) in Nairobi. Total Carbon, Nitrogen, moisture content pH and micronutrients were analyzed using the Test method for the examination of composting and compost(TMECC) methods. The C/N ratio was then calculated to optimize the composting process feedstocks mixture. To profile energy and drying performance, temperature and humidity data loggers were mounted at different locations within the compost reactor and the dehydration chamber. Data analysis was done using the Origin Pro 2018 graphing software. Feedstock characterization established that most of the farm wastes feedstocks had a pH of 5.9-8.0, C/N range of 22:1 to 29:1, moisture content 74 - 92% wet basis (wb).The average pile temperatures reached maximum of 68°C and average of 65 °C within the first 48 hours of composting. The compost heat extractor (COHE), yielded 174 kWh in 205 hours from 1350kg of blended biomass (C/N 28:1) resulting into 0.13 kWh/kg. The coefficient of Performance (COP) of the compost heat extractor was established to be a mean of 74.22 and maximum of 489.9. High COP was achieved because of the low energy consumption of the system auxiliary equipment. The drying chamber temperature and relative humidity conditions of 40 to 60 °C and 40 to 65 %, respectively, were attained therefore providing best conditions for low temperature drying. Cowpea (*Vigna unguiculata*) vegetables leaves were dried from a moisture content of 85 %wb to 10 %wb within 18 hours with thermal efficiency of 62 % comparable to other demonstrated drying technologies. The results affirm the efficacy of food drying with heat from composting of farm wastes. The hybrid solar-thermophilic dryer promises to be a sustainable and cost-effective renewable energy solution to mitigating post-harvest losses on farms in Africa. Further research is recommended to optimize the design of the compost heat exchanger in relation to the dryer sizing.

Keywords: Biomass, Characterization, Compost Heat Extractor, Hybrid, Thermophilic dryer, *Vigna unguiculata*

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LIST OF ACRONYMS AND ABBREVIATION

ABBREVIATION	DEFINITION
A	Surface area
CHRSs	Compost Heat Recovery Systems
COHE	Compost Heat Extractor
COP	Coefficient Of Performance
C_p	Specific heat capacity of the fluid at constant pressure
DC	Drying Chamber
E	Energy content
HAC	Heat Absorption Chamber
KALRO	Kenya Agriculture and Livestock Research Organization
LDPE	Low Density Polyethylene
M	Mass of composting materials
$\dot{m}$	Mass flow rate of the fluid
M_R	Mass of composting reactor
PVC	Polyvinylchloride
SDG	Sustainable Development Goals
TMECC	Test Method for the Examination of Composting and Compost

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Drying is a method of preserving agricultural produce by decreasing the moisture content and water activities from the produce accounting for 10 to 20% of the total industrial energy use in developed countries (Abasi, Minaee, & Khoshtaghaza, 2016; Kemp, 2014). In many developing countries where energy supply is low, reliance on natural sun drying to conserve perishable crops is high. Open air drying however is unhygienic as it exposes foods to soil/dust, foreign matter, rain and other airborne contaminants which enhance the risk of bio-deterioration during storage shortening shelf-life.

Sun drying is the oldest and cheapest method of drying human beings have always used. However, it is ineffective during off sun hours, rain season and at night. In tropical climate, harvest coincides with rainy and wet weather resulting into the destruction of crops already grown. Approximately 30% of post-harvest crop destruction is due to poor drying methods (FAO, IFAD, UNICEF, WFP, & WHO, 2017). Delayed and insufficient dehydration contributes significantly to the accumulation of harmful mycotoxins/aflatoxins in stored produce (Mutegi, Cotty, & Bandyopadhyay, 2018; Wagacha et al., 2010). This among others, is the cause of food crisis in developing and under-developing countries and can be effectively tackled by post-harvest food wastage prevention. Post-harvest losses, has become an important issue because of the increased food demand due to the world population increase beamed at over 10 billion people by 2050 (FAO et al., 2017; UNFPA, 2014). Due to the high moisture content of most of the agricultural products at harvest time, most food products

deteriorate during storage. The possibility of spoilage is omitted by storing the agricultural produce at a safe moisture content level (Chauhan & Rathod, 2018).

Therefore, preservation of food for the afterward use is important. One of the method to achieve this is drying. Drying is a traditional method for food preservation by reducing the moisture content, weight and size of the crop in turn facilitating easy storage, transportation, prevents germination and growth of fungi and bacteria. The main objective of drying is to supply heat energy to the produce at an optimum level in order to maintain the quality of the product without affecting its nutrition value and color at an optimum energy expenditure (Chauhan & Rathod, 2018).

Among the other sources of drying energy is solar. Unlike the conventional drying techniques that utilize expensive fossil fuels, national power grids, etc., solar dryers uses the radiation from the sun. Increased prices, shortages of fossil fuels coupled with the bad environmental effects of fossil fuels, has increased the stress on the utilization of renewable energy like solar energy as alternatives in developing countries and under-developing countries. Solar Energy has the potential to meet the energy demands for drying in the tropical and sub-tropical nations with sufficient solar hours per year (Panchal & Mohan, 2017). Numerous research on solar drying and its shortcomings has been conducted. Throughout the day drying is difficult and might result in food spoilage, drying rate cannot be controlled, slow drying rates during the rainy season and low sun days and contamination due to soil/dust (Green & Schwarz, 2014).

Different researchers have highlighted the need to integrate solar dryers with other sources of energy to prolong drying times. In recent years, different researchers have done some work on the thermal heat source of the composting process ranging from laboratory scale findings (Allen & Chambers 2009) extracting 76 kWh/435 kg, to pilot scale reactors (Bajko et al 2019) attaining a core temperature of 78 °C and commercial and large scale systems (Irvine, Lamont, & Antizar-Ladislao, 2014) generating 7000 to 10000 kJ/kg. A comprehensive analysis of all the work on heat captured from composting process has been discussed and analyzed (M. M. Smith, Aber, & Rynk, 2017).

Therefore, this study adopted the integration of solar and the heat from the compost reactor at thermophilic stage, to prolong drying hours and achieve quality dried produce. The compost wastes could be, utilized for soil amendment, hence playing a double function. An aerobic decomposition of organic materials by bio-microorganisms is a complex Biomass conversion route. It is one of the biomass energy source conversion techniques that generates thermal energy (Christian, Evanylo, Pease, Evanylo, & Pease, 2009; M. M. Smith & Aber, 2014). Biomass contributes approximately two thirds of global renewable energy sources (Allen & Chambers, 2009).

The main objective of this study was to evaluate the efficacy of a hybrid solar thermophilic heat collector for food drying applications. Specifically, it was sought firstly to characterize the suitability of locally available farm wastes for hot composting and secondly to quantify the energy and food drying potentials of a prototype solar thermophilic dryer that has been developed for use on small farms. The study was conducted on a farm in Kitale, Trans-Nzoia County from April 2019 to July 2019. Green grass clippings and weeds, cow and chicken

manure, shredded maize stover and sawdust were sampled locally and analyzed at Kenya Agricultural and Livestock Research Organization (KALRO) in Nairobi. Total Carbon, Nitrogen, moisture content pH and micronutrients were analyzed using the Test method for the examination of composting and compost (TMECC) methods. The C/N ratio was then calculated to optimize the composting process feedstocks mixture. To profile energy and drying performance, temperature and humidity data loggers were mounted at different locations within the compost reactor and the dehydration chamber. Data analysis was done using the Origin Pro 2018 graphing software. Feedstock characterization established that most of the greens had a pH of 5.9-8.0, C/N range of 22:1 to 26:1, moisture content 74 - 92% wet basis (wb). The average pile temperatures reached maximum of 68°C and average of 65 °C within the first 48 hours of composting. The compost heat extractor (COHE), yielded 174 kWh in 205 hours from 1350kg of blended biomass (C/N 26:1) resulting into 0.13 kWh/kg. The coefficient of Performance (COP) of the compost heat extractor was established to be a mean of 74.22 and maximum of 489.9. High COP was achieved because of the low energy consumption of the system auxiliary equipment. The drying chamber temperature and relative humidity conditions of 40 to 60 °C and 40 to 65 %, respectively, were attained therefore providing best conditions for low temperature drying. Cowpea (*Vigna unguiculata*) vegetables leaves were dried from a moisture content of 85 %wb to 10 %wb within 18 hours with thermal efficiency of 62 % comparable to other demonstrated drying technologies. The results affirm the efficacy of food drying with heat from composting of farm wastes.

1.2 STATEMENT OF THE PROBLEM

Agricultural produce post-harvest losses up to 50 percent are due to insufficient good post-harvest practices mostly drying. Weather dependence by open solar drying poses a danger to food security and increases post-harvest food destruction and contamination with soil/dust and mycotoxins. Research into post-harvest conservation techniques for is scant and limited. Production is high during the rainy season and scarce during the dry season. Drying is highlighted as an important process that can address post-harvest losses, a known problem in sub-Saharan Africa (Gogo, Apiyo, Ulrichs, & Huyskens-Keil, 2016; Mutali & Mbugue, 2015).

The moisture content of most farm products, ALV cowpea included depends on the season of the year between 78 and 85 percent. (Natabirwa, Mukiibi, Zziwa, & Kabirizi, 2017). This limits shelf life and creates issues with storage and transportation. Methods in processing and preservation such as open sun and solar drying have been used to dry vegetables such as cowpea (Gogo et al., 2016). The drying time of 9 to 12 hours on hot sunny days and 21 to 24 hours on rainy days have been reported in Uganda to 6.0 to 8.7% moisture content DB (Natabirwa et al., 2017). Usage of fossil powered dryers is also prohibitive due to the cost and technology complications.

These study took advantage of the already existing farm crop wastes, that otherwise could have found themselves in open air composting and contribute to the GHG emission, to generate heat for drying purposes. The byproduct of composting process is a nutrient rich compost manure greatly needed for soil amendment.

1.3 JUSTIFICATION OF THE STUDY

The Hybrid Solar -Thermophilic Heat collector will improve food preservation by improving post-harvest drying techniques. This study looks at the promotion of modern drying techniques to mitigate on the effects of direct sun drying such as soil/dust and mycotoxin contamination. Some of the available drying technologies are fuel intensive, complicated, and expensive for small to medium-scale farmers. Therefore the technology used in this study, aimed at reducing the costs of operating and complication of the drying technology by using readily available fuel in the sun and the crop/other wastes (feedstocks), that are usually burnt or composted openly emitting greenhouse gases (GhG) as shown in Appendix A. The heat, CO₂, NH₃, and H₂O, were regulated during the composting process. This is achievable by means of an enclosed in vessel composting, passively aerated structures that utilize the forced aeration with the chimney effect and constantly monitoring the temperature, C: N ratio and emissions optimized C: N ratio significantly reduces the GHG emission. For a long time now composting for energy, has been investigated upon informally, with results that have not added to the body of knowledge on the subject cohesively, hence the need to encourage research works like this one (Adams, 2005).

Appendix B and C indicate open sun drying in the Philippines and Kenya, respectively. The need to fix cheaper sources of drying energy globally cannot be overemphasized. The solution proposed for this project is a home-based, simple operation and easy maintenance technology. The compost reactor serves as a heat storage facility during days of low sunlight. Simplification of complex composting technologies is the key to this research that contributes to the knowledge gap in science and engineering.

1.4 SIGNIFICANCE OF THE STUDY

Post-harvest agricultural crop spoilage combined with mycotoxin / aflatoxin contamination due to open sun-drying process is a major problem requiring a holistic solution. Fossil fuels energy price spikes, scarcity, environmental impacts (pollution) are not readily available in most developing and underdeveloped countries should be replaced by renewable energy sources, as stipulated in Sustainable Development Goal number 7 (SDG 7) "Affordable Clean Energy," which is directly linked to SDG # 2 "No Hunger."

The United Nations Environmental Program (UNEP) states that the lack of access to and availability of energy resources and environmental transition systems is a limitation on human and economic development. Therefore, increased use of fossil fuels without actions to mitigate greenhouse gases will have global climate change implications. Energy efficiency and increase use of renewables contribute to climate change mitigation and disaster risk reduction. (Spröte, 2019). Energy has been the primary contributor to climate change, accounting for around 60 per cent of total global greenhouse gas emissions, and any production of renewable energy resources is very significant. The SDG Foot 7(a), notes that "facilitate access to clean energy research" is a direct call for this study. This work is so important that it makes use of readily available waste materials in farms that could otherwise have been sources of greenhouse gas emissions. It is also a direct response to poverty alleviation by enhancing food security by drying and prolonging shelf life. Traditional foods in developing countries, such as mushrooms, can be dried and preserved for a longer period in order to improve the health of the population. The combination of solar and composting technology is also essential to the production of healthy compost fertilizer for use as a soil amendment agent.

1.5 OBJECTIVES

The main objective of the study was to evaluate the efficacy of a hybrid solar-thermophilic heat collector for food drying.

Specific objectives

- I. Characterization feedstock of feedstock materials from the study area in Kitale
- II. Design and construct a hybrid solar thermophilic system for drying food or African Leafy Vegetables
- III. Evaluation of the performance of the set up hybrid solar-thermophilic system.

1.6 SCOPE OF THE STUDY

The study focused on the heat capture and analysis from the solar and composting systems. The priority was to assess the compost reactor energy generated and extracted. The tests for no-load and load were evaluated and then compared. The control test used was the electrically heated air in the drying chamber to maintain the temperature between 40 to 57 °C at 35% to 65 % relative humidity. Thermal insulation and the economic analysis of the system was not done.

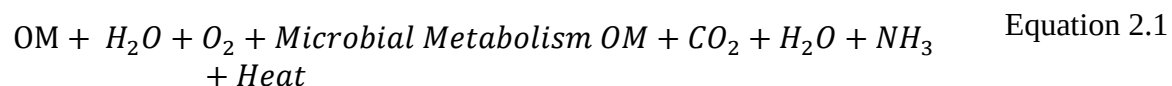
CHAPTER 2: LITERATURE REVIEW

In this chapter, the literature review on composting technology and feedstocks characterization, Solar-drying technology, and drying process technology was covered.

2.1.AEROBIC DIGESTION TECHNOLOGY (COMPOSTING)

Composting is an aerobic method where biologically decomposed organic materials primarily produce compost, carbon dioxide, water, and heat. Typically, conventional composting processes consist of four significant temperature-related microbiological phases: Mesophilic, thermophilic, cooling and maturation, during which the microbial group structure changes with the final product as shown in Figure 2.1. The bio-oxidation of organic material that occurs during composting is an exothermic reaction that continually releases heat, and represented by the general equation in the formula for the composite materials as shown in equation 2.1.

As can be shown in Figure 2.1, the process comprises of the feedstock that should attain conditions discussed in the preceded section to achieve efficient decomposition in the presence of oxygen. The basic formula for the Aerobic composition is shown in equation 2.1.



OM= Organic Matter

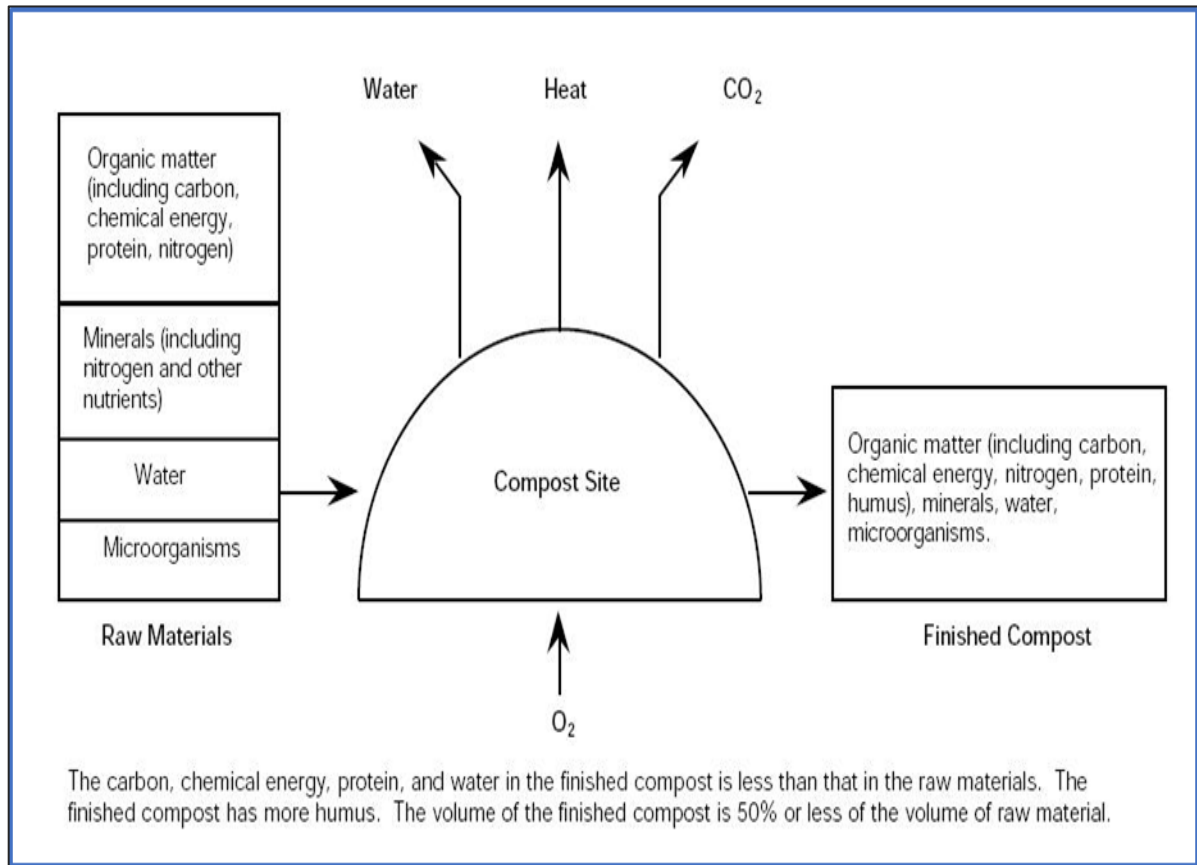


Figure 2.1: Composting process

(Christian, Evanylo & Pease, 2014)

The exact temperature range varies in the literature for what is qualified as mesophilic or thermophilic but generally between 28 °C and 45 °C for mesophilic and > 45 °C for thermophilic. Temperatures will often rise significantly after pile formation and achieve thermophilic temperatures within a few days (Epstein, 2011). The temperatures will rise to the stage where the microbes begin to die (> 71 °C), unless heat is removed oxygen and heat production are highest in this thermophilic stage, as the microbes first target and metabolize the easiest digestible materials such as starches, sugars and fats. The quantity of aeration

required for heat removal can be more than 10 times the microbial oxygenation requirement during this phase (Epstein, 2011; Haug, 1993). Heat extraction acts as goal, to maintain pile temperatures between 54-66°C and prolonging the point of plateau and temperature.

2.1.1. Types of composting systems

The many four methods of composting are; windrows, in-vessel, aerated piles and passively aerated composting systems (Haug, 1993). In the windrows technique, arrangement of materials is the long and narrow stacks piled intermittently and mixed by turning machines. By turning, passive aeration is improved. The supplying air avoids turning in the passively aerated windrow technique with the perforated tubes inserted inside the windrow. Blowers are the most popular technique of the aerated static stack (BCMAF, 1998). Table 2.1, shows the optimum condition for composting.

Table 2.1: Recommended optimal conditions for composting

Condition	Acceptable	Ideal
1 C:N ratios of combined feedstocks	20:1 to 40:1	25-35:1
2 Moisture content	40-65%	45-60% by weight
3 Available oxygen concentration	greater5%	greater10% or more
4 Feedstock particles size	less1 inch	variable
5 Bulk density	454 kg/ m ³	454 kg/m ³
6 PH	5.5-9.0	6.5-8.0
7 Temperature	43-66°C	54-60°C

(Rynk et al., 1992)

2.2.COMPOST AERATION

Aeration was recognized as one of the primary variables that technology can influence during the aerobic process (BCMAF, 1998; X. Wang, Lu, Li, & Yang, 2014). During microbial

activity, which is oxidative in nature, the structure of the air in the mass interspaces changes. MacGregor et al (1981) deduced that carbon dioxide gradually increases in content, thus reducing the concentrations of oxygen. They further established that the average mass content of CO₂ and O₂ is about 20%. The level of oxygen and carbon dioxide ranges from 15% to 20% and 0.5% to 5%, respectively. At oxygen levels below the stated above range, anaerobic factors are triggered influencing microorganisms to exceed aerobic ones thereby causing anaerobic respiration & fermentation to take over (Allen & Chambers, 2009).

The approximate amount of air needed to control the temperature and replenish the oxygen used by the microorganisms is 9:1 air function ratio at 60 °C in the composting stack. A conclusion drawn from the results of 56 different researchers' compost sciences and technology is that, the intensity of microbial activity is indicative of oxygen absorption. The quantity of oxidized carbon determines the quantity of oxygen required, according to scientific theories. However, the carbon content of the waste makes it hard to determine the exact requirement for oxygen since there are two unknown carbon fractions; unknown carbon transformed into cellular bacterial matter and natural carbon refractory which cannot be accessed by the microbes (BCMAF, 1998). Therefore, managing the ventilation process is essential to allowing adequate oxygen supply for aerobic respiration, which in turn encourages heat generation to guarantee decomposition and at the same moment control the temperature by removing excess heat. Table 2.4, highlights the rates of oxygen (l/min/kg. dm) previous researchers analyzed. Kimura & Shimizu (1981b) recorded three aeration levels: low, medium, and high. Increasing aeration rate at low aeration rates (0–1 L / min. kg-DM) improved the peak temperature, dry matter loss and complete weight loss.

Table 2.2: Ranges of aeration used in previous studies

RANGE(L/min.kgdm)	STUDY	YEAR (Shimizu, 2017)
1 0.2-1.4	Schulze	1962
2 0-0.1	Lau et al	1992
3 0.25-1.3	Doshu	2003
4 0.2-2.7	Kimura et al	2007
5 0.09-0.5	(Shimizu et al., 2018)	2017

There was greater weight and dry matter loss for medium aeration rates (1–5 L / min. kg-DM), but composting temperature was smaller than low aeration rates. Fermentation was slow at elevated aeration rates (> 5 L / min. kg-DM).

2.2.1. Types of Aeration Methods

Aeration generally is carried out by passively or forced air movement (Shimizu, 2017). Passive aeration takes place naturally using natural air movement while forced aeration uses fans to push the air through the pile (Pitschel & Lowry, 2016).

Passive Aeration

Passive aeration is normally applicable in compost systems that are periodically agitated or turned. The turning process helps in air refreshing in the pile even if this air is quickly consumed by the process of composting (Haug, 1993; Shimizu, 2017).

Forced Aeration

Forced aeration may be constant, enhanced aeration rate, or intermitted switch on or off, depending on the compost system type. In the continuous aeration process, the required air

flow rate is reduced, reducing the fluctuation in oxygen and temperature levels (Shimizu, 2017). Continuous aeration can trigger gradients in the composting blend that can result in excessive drying and cooling in areas where air entered.

2.2.1.1. Design consideration for aeration

It is highly recommended that aeration systems require long lengths of piping and in some cases use perforated lengths instead of still pipes to distribute air within the compost pile system (Keener, Hansen & Elwell, 1997). Critical selection of piping diameters is key to reducing pressure drops in the aeration system and that entails total analysis of the compost system (Keener et al., 1997).

2.2.2. Basic compost ingredients

The feedstock for decomposition can be characterized by knowing its nutrient composition (Epstein, 2011). The quantity of nutrients available to the microorganisms, in the substrate, its concentration and its quality, plays a major role in the efficiency performance of the composting and the quality of the products (Phillip, 2010). These macronutrients consumed by microorganisms include, carbon (C), nitrogen (N), phosphorous (P) and potassium (K) (Epstein, 2011). Among the most important nutrient ratios in the composting process is the ratio between carbon and nitrogen content (C:N) (Bajko et al., 2019). Normally, more carbon is required than nitrogen is important to the microorganisms involved in composting. The recommended C:N ratio is from 20-30.(on a mass basis) (Epstein, 2011). The significance of achieving the C: N ratio in a compost matrix is that, above the required quantity of carbon,

the composting process will be slow. Meanwhile, excessive nitrogen will enable the production of NH_3 and N_2O at higher levels. This may cause odour problems.(Phillip, 2010).

Sources of high carbon and nitrogen materials

The sources of high carbon materials good for composting are; falling leaves, straw (maize stalks), tiny wood chips or sawdust, rice straw, maize cobs and other browns (Haug, 1993).

The sources of high Nitrogen materials good for composting are; fresh kitchen wastes (only plant origin and no oils or fats), fresh grass clippings, coffee grounds, manure (from cow, sheep, chickens or goats), feathers and alfalfa meal(Ayre, 2002).

Water and air

For microorganisms to live and do their work well during composting, the pile needs to be neither sopping wet nor too dry. Ideally it should be about as wet as a wrung-out sponge.

The heat generated in the composting process is dependent on the rate of aeration. The air amount available for the aerobic microorganisms is important and related to the rate of the composting (Jindal & Ratanamalaya, 2006). The amount of air present and penetrating in the mass of the composter affects the temperature distribution. The higher the aeration rate, the lower the maximum temperature in the composting pile, but the faster the rate of temperature rise because the microorganisms are air loving (Jindal & Ratanamalaya, 2006). The biomass feedstock nutrients are site and type specific hence the recommendation of, characterization of feedstocks before composting to be aware of the chemical composition and physical structure with the parameters.

2.2.3. Availability of biomass feedstocks

The Ministry of Environment and Forestry highlighted that Kenya generates approximately 22,000 tons of waste every day. Approximately 60 % of the waste is from rural areas. Past studies indicate that 60 % to 70 % of the waste produced is organic, 20 % is plastic, 10 % is paper, 1 % is medical, and 2 % is metal. Kenya has signed a number of international conventions and multilateral waste management related agreements (MEF, 2019).

The farm households in rural communities generate solid wastes such as manure, tree trimmings, grass clippings, and crop residues. Of the total solid wastes generated in any farm household, 80% are organic in nature (Mohee, 2007). Livestock generates large amounts of manure wastes amounting to 5.27 kg/day/1000 kg live weight based on a wet weight (Mohee, 2007). If this manure mostly animal produced ones are not properly managed or left untreated, the result is so telling on the soil degradation, water and air quality, creation of breeding medium for flies and other insects. Uncontrolled decomposition of any wastes generates odorous gases, ammonia volatilization, leading to the formation of acid rain. The source of the most frequent complaints animal producers face are the odours generated at the production and storage facilities (Wright, 1998; Mohee, 2007). Moreover, compromised the soil quality due to potassium, phosphorous and other nutrients over loading is possible.

Due to highly organic wastes generation in Kenya, feedstock raw material is readily available

2.2.4. Feedstock characterization process

In order to achieve great results from the composting process, the feedstock chemical and physical composition knowledge is important through the characterization process. Sampling is the first and most important tool to obtaining accurate results from characterization.

(Drosg, Braun, Bochmann, & Al Saedi, 2013). The rationale and main steps of the methodology require pre-clarification by understanding the purpose of the inquiry, the origin of the material, the anticipated features of the sample, the place from which the samples were gathered and the time/weather variation. Parameters to be analyzed should be clear (Drosg et al., 2013). A representative sampling method is highly recommended because the greatest error emanates during the sampling phase (Esbensen, Julius, Holm-Nielsen, Mortensen, & Friis-Petersen, 2007). Additional sampling, packaging, storage and transportation processes are described in (OME, 2012).

2.2.5. Compost Feedstocks and Compost test method

The American Composting Council has developed the Test Methods for the Examination of Composting and Compost (TMECC), which offers information for the procedures of the composting sectors and verifies the physical, chemical and biological condition of composting feedstocks, materials been composted (process) and at the point of use and sale (A &L, 2018). Table 2.3 shows some of the analytical methods.

Table 2.3: Analytical Methods for compost feedstocks and composts

Analyte	Methods/Standard
% Solids, % Moisture	SM 2540 G (Dried at 105°C overnight)
pH	TMECC 4.11-A(1:5 w:w slurry)
Total P, K, Ca, Mg, S, Na, Cu, Zn, Mn, Fe, Al	TMECC 4.05. (Microwave assisted acid digestion) ICP
Organic Matter	TMECC 05.07-A (Loss on Ignition)
Total Nitrogen	TMECC 4.02-D(Combustion)
Bulk Density	TMECC 3.01-A
Particle Size	TMECC 5.08-B
Water holding capacity	TMECC 3.01-A
% Volatile Solids	Ashed at 550C (Method 2540)

(Peters et al., 2003)

2.2.5.1. Proximate analysis

The method of proximate analysis has been reported to be used to determine the moisture content in banana peels by using the oven dry method [SM 2540 G (Dried at 105 °C overnight)]. Drying of the holding dishes achieved by preheating them in a drying oven at 105 °C for an hour and then uses the desiccator to cool them and individual empty weights noted afterwards. Samples thereafter added to the dried dishes and weights noted before been inserted into the drying oven at 105°C for 12 hours before been placed in the desiccator for cooling and then reweighed. The moisture content was reported as the weight lost and calculated using equation 2.2 (Kabenge et al., 2018).

$$\text{Moisture content(\%)} = \left(\frac{W_m - W_d}{W_m} \right) \times 100 \quad \text{Equation 2.2}$$

Where, W_m is the start sample weight, as W_d final dried sample weight.

2.2.5.2. Ultimate analysis

Total Nitrogen content (TNC) analysis using ultimate analysis by the Calometric method with the Block Digester (BUCHI) system K-437 model was reported. By using equation 2.3, Total nitrogen content was calculated.

$$\%N = \frac{(a - b) \times v \times 100}{1000 \times w \times al \times 100} \quad \text{Equation 2.3}$$

Given; "*a*" to be nitrogen concentration in the solution, '*b*' is N concentration in the block digester, *v* is total volume at the end of analysis procedure, '*w*' is weight of the dried sample and '*al*' is a liquid of the solution taken (Kabenge et al., 2018).

Total Nitrogen, Total solids, VS, pH, total Kjeldahl nitrogen (TKN) can also be analyzed to the APHA standard methods (X. Wang et al., 2014). By dividing the TOC by the TNC, the C: N ratio can be, calculated using Equation 2.4.

$$\frac{C}{N} = \frac{W1 \times C1 + W2 \times C2 + W3 \times C3}{W1 \times N1 + W2 \times N2 + W3 \times N3} \quad \text{Equation 2.4}$$

Where; W1, W2, and W3 where the volatile solids (VS) by weight in a one substrate of the mixture, whereas. C1, C2, and C3 are organic carbon content in g/kg VS in each substrate. N1, N2 and N3 were TON present in each substrate in g/kg VS (X. Wang et al., 2014). The lower the C/N ratio, the higher the ammonia concentration and slower the composting process (Rynk et al., 1992). From the literature, Table 2.4 shows the C/N ratio for different kinds of materials.

Table 2.4:(C/N) of common composting materials (Rynk et al., 1992)

Feedstock type	C/N Ratio	Material	C/N Ratio
Cattle Manure	19:1	Poultry Carcass	4:1
Cattle Carcass	10:1	Sawdust	442:1
Corn Silage	40:1	Sheep Manure	16:1
Corn Stalk	68:1	Swine Carcass	14:1
Dairy Manure	20:1	Swine Manure	12:1
Grass Clippings	17:1	Turkey Litter	16:1
Horse Manure	30:1	Wheat Straw	127:1
Leaves	54:1	Wood Chips	600:1

Upon characterization, the C / N ratio, moisture content, pH, bulk density and micro / macro feedstock structure are calculated and evaluated.

2.2.5.3. Mathematical modelling of the feedstock composition

The Food and Agriculture of Canada recommended the following mathematics models to for C/N ratio and the moisture content determination in order to blend the materials in suitable proportions otherwise known as the recipe.

C/N Calculations formula

$$C:N = \frac{\text{weight of C in ingredient } x + \text{weight of C in } y + \text{weight of C in } z + \dots}{\text{weight of N in } x + \text{weight of N in } y + \text{weight of N in } z + \dots}$$

$$C/N = \frac{[\%C_x \times x (1-M_x)] + [\%C_y \times y (1-M_y)] + [\%C_z \times z (1-M_z)] \dots}{[\%N_x \times x (1-M_x)] + [\%N_y \times y (1-M_y)] + [\%N_z \times z (1-M_z)] \dots} \quad \text{Equation 2.5}$$

Moisture Calculations Formula

The following expression was applied (BCMAF, 1998).

$$\text{Moisture Content} = \frac{(x \times M_x) + (y \times M_y) + (z \times M_z) \dots}{x + y + z + \dots} \quad \text{Equation 2.6}$$

Where:

x = total weight of ingredient , z = total weight of ingredient z , M = desired mix moisture content, M_x , M_y , M_z ... = moisture content of ingredients x , y , z ... (Dry weight basis).

$\%C_x$ $\%C_y$, $\%C_z$... = %carbon of ingredients x , y , z ... (Dry weight basis).

$\%N_x$ $\%N_y$, $\%N_z$... = %Nitrogen of ingredient x y z ... (Dry weight basis).

2.2.6. Types of compost heat recovery systems (CHRS)

Three mechanisms of heat extraction from pile decomposition were discussed (M. M. Smith et al., 2017). Simple hotbeds used in China 2,000 years ago, using pile conduction otherwise known as, Hydronic, Jean Pain Methods and latent evaporation heat (Bajko et al., 2019; Pellaton, 1972).

2.2.6.1. Simple hotbeds used in China 2000 years ago

Direct use where plants were cultivated above the composting stack was implemented. The composting mass delivered heat straight through convection to the plants' root area. In France around the 1600s, where hotbeds fenced with glass were used for crop manufacturing, further development of this technology was seen. This method consisted of a trench filled with composting fertilizer coated in topsoil to enhance crop growth, like was the case in the Chinese utilization. Heat generated from the composting manure, through convection, rose, warmed the roots of the crops and prolonged months of growing plants through the spring and fall (M. M. Smith et al., 2017). In the early 1900s, the Automotive Industrial Revolution (AIR), which saw the replacement of the use of horses as a mode of transport with vehicles, caused feedstock shortages and this technique declined (M. M. . M. Smith & Aber, 2018).

2.2.6.2. Jean Pain method

Jean Pain pioneered the second method for heat recovery from composting at his farm in France in the 1970s, based on conduction (M. M. Smith & Aber, 2014). He used a 55-ton chipped brushwood pile with hundreds of meters of coiled tubing inserted into the composting mass to heat water from 10 to 60 °C for a period of six months at a pace of 3.8

litres / minute. Then the water was used to heat a high tunnel and a farmhouse (Pellaton, 1972). The capacity to produce heat and heat the water using the thermal mass in this technique has made it commonly used and is still used (M. M. Smith & Aber, 2014).

2.2.6.3. Limitation of the Jean Pain Method.

More appropriate for backyard activities owing to the need for work during installation and removal of the tubes during pile construction and breakdown, which could lead to deformation of the tube. Not appropriate for business activities where the objective is to generate revenue and to account for labour / time. Too much heated water removal or substitute water is too cold, can inhibit microbial development and can collapse the microbial population (M. M. Smith & Aber, 2014). However, conduction-based CHRSh can be of excellent use for small-scale activities under good management. (Pipes integrated in composting mass may be substituted by recirculating heat exchange tubes in composting feedstocks, which can be used commercially with big amounts of biomass. In New Brunswick, Canada, this form of technology is being used to avoid snow and ice frowning (M. M. Smith & Aber, 2014).

2.2.6.4. Latent heat of vaporization

Since more than 60% of the energy produced in a composting stack is stored in the water vapor, these systems recover significantly more energy than convection or conductive systems. These structures use a blower to extract heated compost vapor from the decomposing feedstocks through a network of aeration tubes below the composter. The

heated vapor is transmitted from here through a manifold and into a heat recovery unit for vapor condensation that warms water for hot water needs. Therefore, the heat released during composting takes essentially two forms; sensible heat (energy associated with an increase in temperature) and latent heat (energy associated with an increase in water vapor). Recovering heat from compost materials is possible and can reduce the cost of drying or heating requirements.

2.2.7. Composting Heat Recovery principles and applications

Three stages of heat recovery from composting, heat production, heat capture and heat utilization is considered (M. M. Smith & Aber, 2014; M. M. Smith et al., 2017). These stages are highly dependent on each other. The ultimate available energy from a composter substrate is the same as the energy from substrate combustion and determinable calorimetry process. Composting is far from fully oxidizing the organic compounds and releasing the inherent energy in it (Epstein, 2011). A literature review of various compost feedstocks, found the average heat production rate to be 19.44 MJ/kg dry matter (DM); Lab-scale systems: 1895 kJ/hr ($s = 1606$ kJ/hr) for lab-scale and for pilot scale systems, 20,035 ($s = 16,505$ kJ/hr). The quantity of energy (Q) that air carries out depends on the change in enthalpy (h) and air mass flow rate ($\dot{m}$). By equation it can be calculated;

$$Q = \dot{m} (\Delta h) = \dot{m} Cp(h_2 - h_1) \quad \text{Equation 2.7}$$

Where; Q =Energy carried by Air , (Δh) = Change in Enthalpy, h_1 = enthalpy of the air or water entering the system (e.g., ambient air), h_2 = the enthalpy of the air or water leaving the

system, ($\dot{m}$)=Mass flow rate of Air or water depending on the media of heating used and C_p is specific heat capacity of the heat carrying medium (M. M. Smith et al., 2017).

2.2.8. Heat Extraction from the compost (CHRs)

In this study, focus is on the Hydronic systems run by a mechanical pump. Adams (2005), highlights that the amount of heat present from the compost is dependent upon the technique used for its recovery from the process. Recovery by forced air is more efficient in the in-vessel operations. Losses due to the compost mass configurations and manipulation are also highlighted (Adams, 2005).

Donal P. Chambers (2009), designed a Compost Heat Extraction Unit (HEU), to extract heat from the composting system for a variety of utilization. His system efficiently heated a 60 kg water tank for 32 days achieving a maximum water temperature increase of 36.5°C, a total energy of 76 kwh recovered at a 5.7 kg/kWh rate from a 435 kg capacity compost pile. The HEU achieved a 6.8 coefficient of performance (COP) at a 3kWh/day heat recovery rate and was calculated using equation 2.8.

$$\text{COP} = \frac{\text{Energy Extracted}}{\text{Energy Consumed}} \quad \text{Equation 2.8}$$

Pitschel & Lowry (2016), achieved heat recovery at the Gibbs House Compost Heat Recovery facility facilitated by the Western Michigan University and provided temperature to the soil between the ranges of 4°C to 21°C (Pitschel & Lowry, 2016). In all the compost

system studies and analysis, continuously temperature measurements inside the compost mound or reactors acted as a means of observing and capturing data (Bajko, Fišer, & Jícha, 2018).

2.2.9. Compost heat generation, extraction and principles

Heat extracted and the rate of decomposition determines the energy balance of the system (Haug, 1993; Neugebauer, Sołowiej, & Piechocki, 2014). Heat stored in the compost (q_s) is calculated by knowing the rate of thermal generation (q_g), dry air sensible heat (q_a) and latent heat of water (q_w) into and out of the compost system and heat loss from the reactor wall (q_i) (Keener, Ekinici, Elwell, & Michel, Jr, 1991). Therefore the energy balance will be;

$$q_s = q_g + (q_a + q_w)in - (q_a + q_w)out - q_i \quad \text{Equation 2.9}$$

Or

$$\frac{d(mcT)}{dt} = Q_{in} - Q_{out} + Q_{trans} \quad \text{Equation 2.10}$$

Where;

The left side ($\frac{d(mcT)}{dt}$) indicates the sensible heat of the composting weight of mass. Q_{in} is a combination of heat gained from solar and enthalpy due to the incoming air, Q_{out} is heat losses via system environment through conductive, convective and radiative losses, enthalpy of incoming air and heat taken away by the heat exchanger, Q_{trans} is the microorganisms induced biochemical reactions happening during the composting period and are either exo or endo-thermic (Bajko et al., 2018). The ingredients used in the compost materials determine the compost mix's specific heat capacity. The total Energy produced is the sum of the heat

produced over time. Irvine et al (2014) reported temperatures reaching above 60 °C in 24 hours' time similar to Kamil Ekinci (2001)

2.2.10. Design consideration for compost reactors and CHRS

In their research on CHRs Bajko et al (2019), used thermodynamics equations to calculate the cumulative heat generated and extracted from the composting system. The feedstock mixture and composition is key to the compost reactor design (C/N), moisture content, pH and aeration as stated before. The discharge flow rate of the heat transporting fluid is important to find an optimum amount of heat that could be recovered from the compost without negatively affecting the composting heat profiles and processes. This is to prevent total cooling of the composting matrix. For the CHRS, the transporting medium such as stainless steel, Antizar-Ladislao et al (2010), low density polyethylene (LDPE) pipe, Bajko et al (2019) and copper pipes, Allen & Chambers (2009) have been utilized (Allen & Chambers, 2009; Antizar-Ladislao, Irvine, & Lamont, 2010).

2.2.11. Hybrid solar/compost heat systems

The findings of a feasibility study on an hybrid solar and low grade compost heat, found that composting heat raised the air temperature in the chimney's input area 2.12.MW (34%) of the 6.24 MW produced power (Anderson, Shafahi, & McNamara, 2015). A compost waste heat to energy solar chimney power plant (SCPP) was designed with the potential to generate 100 MW with the annual potential revenue of \$83M (Anderson et al., 2016).

2.2.12. Utilization

The slurry lagoon with a heat exchanger and pump, 540 m³ extracting 6.5 kWh energy, heated water at 55 °C and supply it to the radiators (Hughes, 1984). With a fan driven heated air from compost to the soil, Fulford (1986) heated a greenhouse producing fruits to temperatures between 13 to 19 °C. A weaner house, was heated by a 24 m³ cylindrical of slurry reactor generating 149 kWh/day (Svoboda & Fallowfield, 1989). Elsewhere, greenhouse-heating using a reactor with chicken manure, rice bran, sawdust and an air blower with a heat exchanger extracting 0.17 kWh/day, was reported (Seki & Komori, 1987). Heinonen et al (2005), using cattle slurry and Jam waste filled reactor, have reported pre-heating water to 50 °C using a plate exchanger for washing farm equipment. By composting military food wastes in a within in-vessel composter, water heated to 49 °C was reported (Allen & Chambers, 2009).

2.2.13. Conclusion on the composting technology

From the literature reviewed, composting systems heat generation and extraction technology is theoretically and technically, proven to be a cheaper source, albeit labor intensive, but also less challenging for rural people to operate without prior technical training. The waste product is compost, very rich in nutrients important for soil enrichment and can be a game changer in reducing the agricultural production costs in developing country that fully depends on imported fertilizers. In addition, the integration of another energy source such as Solar Energy with the energy generated from the composting process (Hybrid) would increase the efficiency of the system and provide equalization of the energy demand by the microorganisms responsible for the composting process.. In order to explore the potential for

integrating solar energy systems with composting the next section reviews the solar drying systems.

2.3.SOLAR DRYING SYSTEMS

Solar drying is the type of drying that depends on the sun radiation. The direct sun drying is a common, oldest, and economical method for drying of food materials in the developing countries. Most African countries experience a higher level of solar radiation of more than 2,500 hours throughout the year (Diabaté, Blanc & Wald, 2004). Nevertheless, much of the radiation is lost due to heavy precipitation and cloud cover. This constant precipitation results in moisture, which slows down the drying of various foods. Farmers from developing countries face almost the same problem of insufficient conservation technologies; thus, most agricultural products with high moisture content are disposed off annually due to decomposition by microorganisms. Some farmers use dehydration as a food preservation method, the downside of which is very low drying rates. This method requires a large open area and depends on weather conditions. Uneven drying, mixing of dust, dirt and infection with insects and microorganisms results into poorer quality of open sun-dried products. Figure 2.2 contrasts open sun drying and conversion solar-drying systems showing that open sun drying has longer drying times compared to solar drying methods (Panchal & Mohan, 2017).

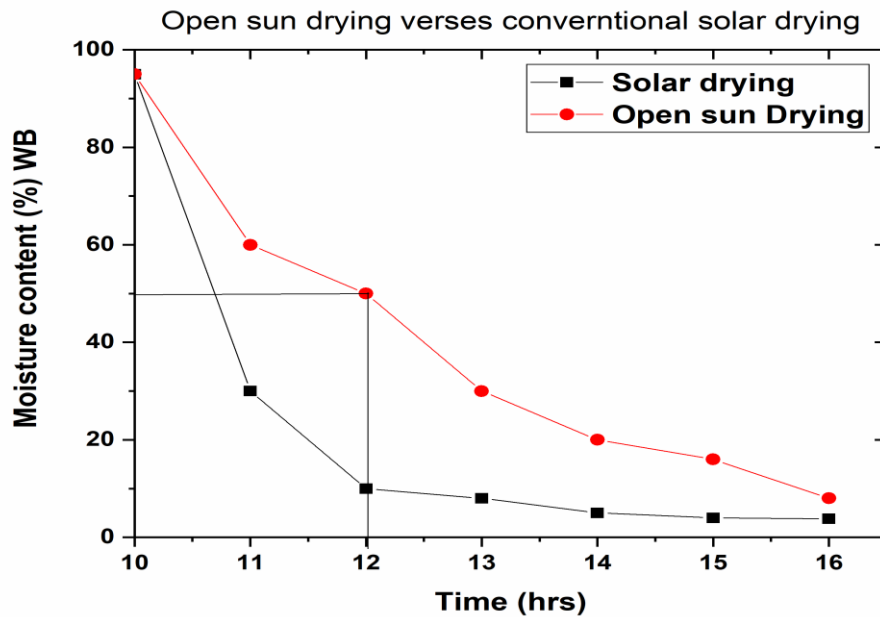


Figure 2.2: Open sun drying verses convention solar drying

(Panchal & Mohan, 2017).

As can be seen in Figure 2.2, moisture removal is fast in conventional solar drying systems. After 12 hours of drying, open sun drying removed 45 % as compared to 85 % in conversion solar drying systems. Solar drying, as an alternative to open and direct sun drying as shown in Figure 2.3, is a promising option for the drying of fruits and vegetables in developing countries. Mechanical drying, mostly used in industrialized countries, is not accessible to small farms in developing countries due to high investment, operating costs and limitation of the technology used that requires prior training and practice (Kalogirou, 2018).

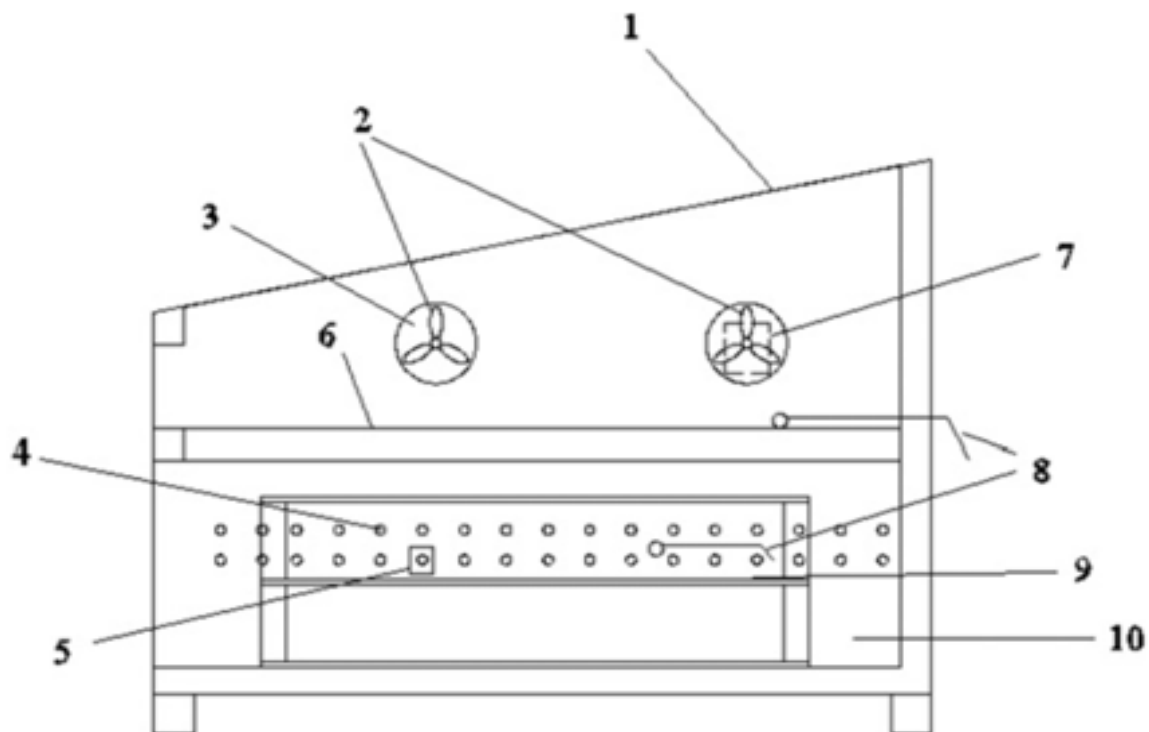
2.4.Types of solar drying technologies

Solar dryers are categorized by design as direct and indirect dryers, by air movement through the drying systems as active and passive dryers. In natural convection solar dryers, the air

flow is due to the buoyancy of the induced air pressure, whereas in forced solar dryers, the air flow is supplied by a fan powered by electricity, solar module or fossil fuels fossil fuel (Al-neama & Farkas, 2018).

Indirect solar drying technology

This system has a separate drying chamber and a solar collector. Components such as solar collector, drying chamber, a fan in active and an air ducting system are incorporated to ensure air circulation. Better product drying and efficiency of the drying is of paramount importance. The drying air can be recirculated to promote drying process effectiveness (Al-neama & Farkas, 2018). Figure 2.3 shows a schematic diagram of an important parts of a solar dryer.



1-Glazing, 2-Fans, 3-Air inlet, 4-Exit of Air, -5-Humidity probe, 6- Dryer absorber plate, 7-Velocity probe, 8-Temperature sensors, 9-Perforated tray, 10-Drying chamber

(Al-neama & Farkas, 2018)

Figure 2.3: Schematic drawing of a solar dryer

2.4.1. Hybrid solar systems drying systems

A hybrid-powered solar system with DC fans in the collectors powered by either 120W solar modules or 300W with a turbine and an AC fan with an area of 100 m² was developed and tested. Results indicated that the dryer was effective for drying fruit and that the solar drying time was one third of the natural sun drying system (Zhong, Li, Wu, Yu, & Tang, 2012). In addition, an indirect type of natural convection solar dryer with integrated collector storage of solar and biomass backup heaters, was designed, constructed using locally available basic materials and evaluated. Tested in three phases: solar alone, biomass alone and mixed solar and biomass by drying pineapples.

The results indicated that the device was very successful for fruit drying, and for most of the materials to be dried, the solar drying time was only one third of that needed in the natural sun drying process. Therefore, due to solar time intermediacy, hybrid systems work more efficiently than stand-alone systems.

2.5.DRYING PROCESS TECHNOLOGY

In any drying process, the two most important factors are heat energy and airflow. The heat energy evaporates the moisture from the inside of the dried material and is transported by the airflow. Two significant steps characterize the drying process of any agricultural product:

migration of the moisture from the inside of the item to the ground and evaporation of the same moisture from the ground to the surrounding atmosphere. The technology of drying relies on both external and internal factors. External factors require drying media temperature, humidity, and velocity in the external setting. Internal factors are: surface features (texture), chemical composition, physical (porosity, density), size and shape of the item to be washed (Hossain, Amer & Gottschalk, 2009; Zhong et al., 2012).

Drying materials are broken down into hygroscopic and non-hygroscopic materials. Hygroscopic materials dry to zero moisture content because of the closed capillaries or surface forces, the moisture content is bound and remains in the material. Non-hygroscopic can be dried to zero moisture content because the moisture can be absorbed or the surrounding air is loose and depends on the relative humidity of the surrounding air. This affects the rate of drying which differs depending on the material structure (Hossain et al., 2009). When the water vapor pressure in the product becomes equivalent to the partial air pressure in the external setting, the moisture content of equilibrium (M_e) is achieved (Abasi et al., 2016).

2.5.1. Drying characteristics curves

Figures 2.4 and 2.5 show the variation in the moisture content of the material with relative humidity of the surrounding air, showing the bound and unbound moisture content of the product and the average time moisture content (drying rate) respectively (Ekechukwu & Norton, 1999).

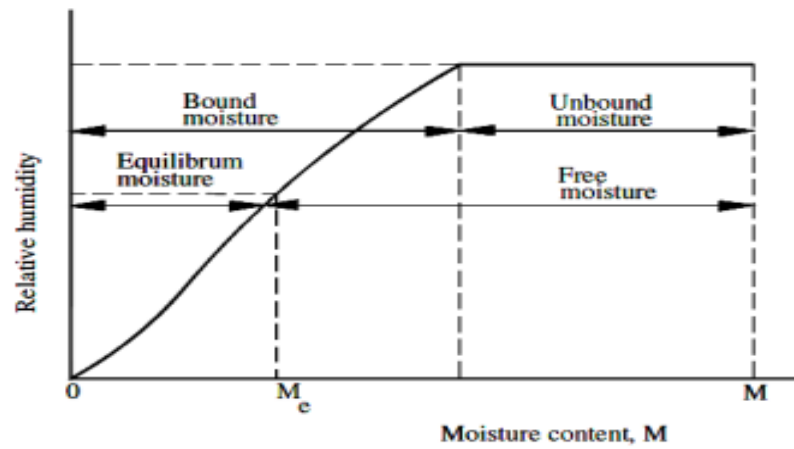


Figure 2.4: Relative Humidity versus Moisture in the drying material

(Mumba, 1995)

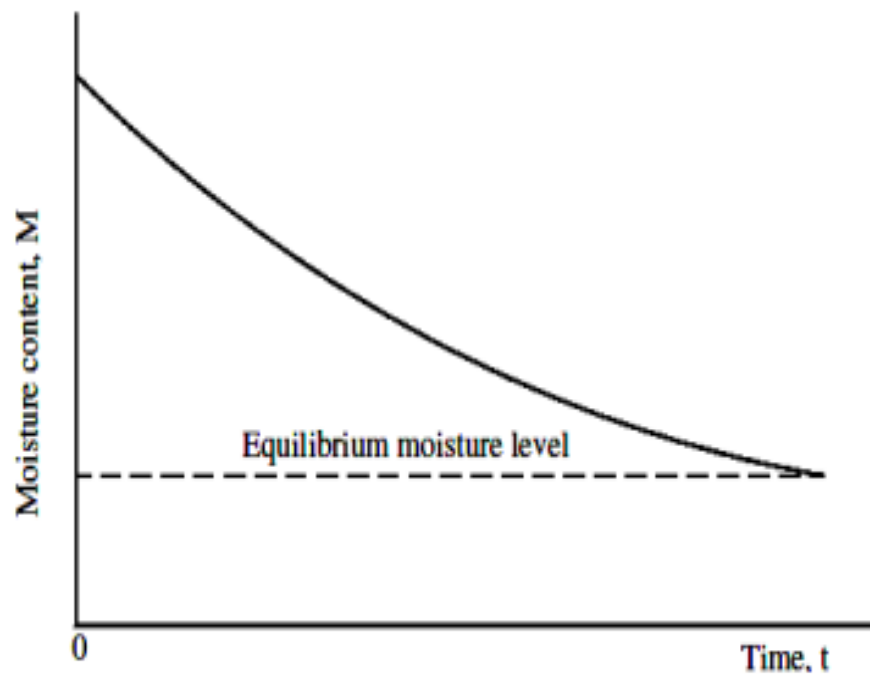


Figure 2.5: Moisture loss rate Curve

(Mumba, 1995)

For both hygroscopic and non-hygroscopic materials, the change in drying rate with moisture content is shown in Figure 2.6. A constant drying rate that ends at a critical point proceeded over by the falling drying rate is common in both materials. The region is the same for both hygroscopic and non-hygroscopic materials in the constant drying rate. The dropping drying period varies. There is a uniform decreasing drying rate of non-hygroscopic products until the moisture content is zero. The falling period for hygroscopic materials is similar until the unbound moisture is completely evaporated and the drying rate becomes zero when the equilibrium is reached (Mumba, 1995; Nwakuba, Asoegwu, & Nwaigwe, 2016).

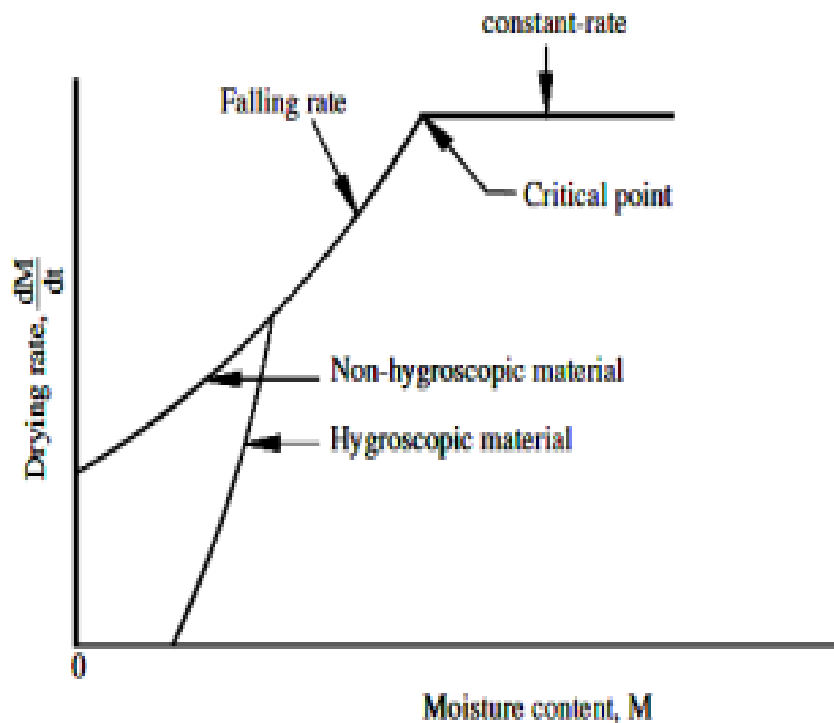


Figure 2.6: Moisture content versus drying rate.

(Mumba, 1995).

2.5.2. African Leafy Vegetables (ALVs) drying characteristics and energy requirement

African leafy vegetables (ALVs) are leguminous plants used as vegetables in major components such as succulent stems, very young fruits, flowers and leaves. They are multifunctional plants, a source of high dietary value food for humans and livestock, and many health advantages (Mutali & Mbugu, 2015). Cowpea otherwise known as *Vigna unguiculata* (L) Walp (Family: Leguminosae), is one of the most important food grain legumes grown for both leaves and bean consumption in the savannas of tropical Africa, Asia, Europe, Central and South America. Production is said to have steadily increased over the past 30 years, supplying food for 52 % in Africa, animal feed for 13 %, seed for 10 %, (Raji & Olanrewaju, 2015).

In Kenya, a number of leafy vegetables present are enormous. 200 varieties have been documented sadly only 20 have been recognized (Herforth, 2011). In Trans-nzoia, Kitale county area, Cowpea is one among the other ALV grown for both leaf and bean utilization as food for human beings and animals. Traditionally, the ALV are preserved (45 %) by sun drying, (35 %) by fermentation (Mutali & Mbugu, 2015). Simple hydrating by sprinkling with water to enhance vegetable freshness for a short period is another method (Gogo et al., 2016). The adverse impacts of this technique are poor quality yield from traditional drying techniques owing to dust, rain, wind, insect attacks, rodents and domestic animals (Kiremire, Musinguzi, Kikafunda, & Lukwago, 2010).

ALV's 50 percent post-harvest losses, are due to insufficient good post-harvest practices. Research into post-harvest conservation techniques for ALVs is scant and limited. Most ALVs production is high during the rainy season and scarce during the dry season. It is important to use adequate techniques to preserve these vegetables throughout the year. ALVs drying is highlighted as an important process that can address post-harvest losses, a known problem in sub-Saharan Africa (Gogo et al., 2016; Mutali & Mbugu, 2015).

The moisture content of most ALV, depends on the season of the year between 78 and 85 percent (Natabirwa et al., 2017). This limits shelf life and creates issues with storage and transportation. Open sun and solar drying have been used to dry vegetables such as cowpea (Gogo et al., 2016). The drying time of 9 to 12 hours on hot sunny days and 21 to 24 hours on rainy days have been reported in Uganda to 6.0 to 8.7% moisture content DB (Natabirwa et al., 2017).

2.5.3. Energy Requirement for drying some of the ALVs

The energy required to dry some of the vegetables at different temperatures was calculated (Mutali & Mbugu, 2015). Cowpea leaves took 304 minutes to dry to 15 % wb and consumed 168 J/g at 100°C and 11.2 J/g at 40°C using a calibrated standard laboratory convective dryer (High efficient thermal insulated) (Binder, 0.5 m/s air speed, 0 to 125°C temperature range, in Nairobi

2.6. SUMMARY OF KEY RESEARCH GAPS

The global food losses and wastes estimated at 1.3 billion metric tons, equivalent to over 30% of the total food generated, for human consumption, and the waste could feed around 1.6 billion individuals annually. A total quantity of 100 metric tons of food is estimated to be lost in Africa, and the value of post-harvest loss is estimated at approximately \$4 billion for grains alone (FAO, 2018). Post-harvest losses, are attributed to delayed and insufficient dehydration resulting into the accumulation of harmful mycotoxins/aflatoxins in stored produce. Cheaper and easy conventional drying systems are not readily available in most of the rural setups, causing the loss of seasonal fresh, traditional foods such as the ALVs and mushrooms.

Limitation of Solar Drying

The successful solar drying must include many additional factors, such as local climate, variety of biological materials, drying product quantity etc. Drying is quicker during the day and slower during the night (Al-neama & Farkas, 2018). Therefore, the incorporation of thermal energy from the decomposition of biomass at the thermophilic stage into solar collectors is intended, to improve drying efficiency. This is because in a hybrid solar dryer, back-up heat and energy storage power tends to dry during sunlight hours. In this document, a proposal is to design a Hybrid Solar and Thermophilic (composite) heat collector. This is to tap in and collect the heat generated during the thermophilic stages of the decomposing materials. The aim is to provide prolonged drying hours in a day even during the off-sunshine hours and low solar irradiance periods.

In order to mitigate this issue, energy from the composting process exceeding 65 °C can complement solar drying in the low temperature drying of food processes. However, the intermittence and inconsistency in the technology inhibits quality and faster food preservation. It has also been shown that the substantial quantities of the thermal energy generated from the composting process normally goes to waste and the technology of biomass energy transformation through aerobic process, is the least researched on. SDG 7 encourages research in clean and sustainable energy for all. The high temperatures attained during the composting process as shown in the literature can be extracted and be used for the drying, green house heating in winter, building heating and other agricultural uses. The by-product (compost) is a soil amendment resource.

CHAPTER 3: MATERIALS AND METHODS

The following chapter describes the methods used to create and install all components of the hybrid solar thermophilic heat recovery and drying system. The approaches used for each specific objective, are shown in Figure 3.1 and discussed as sections.

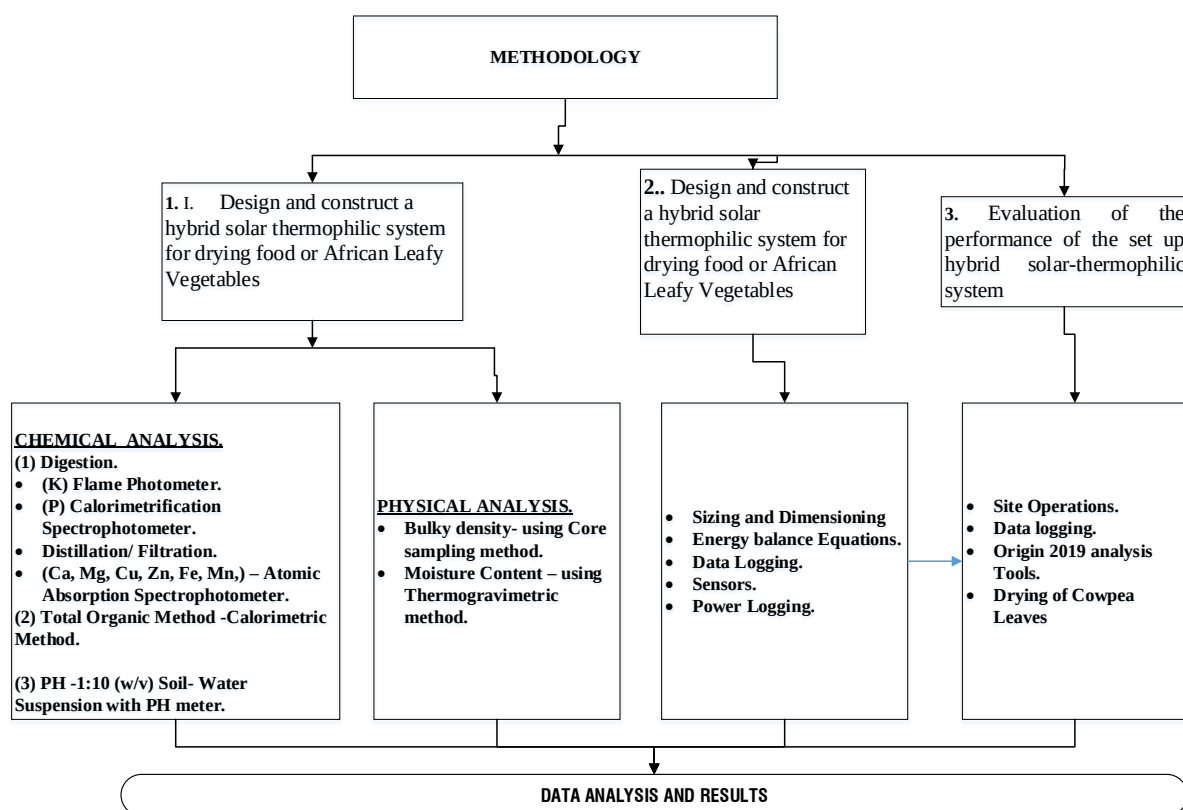


Figure 3.1: Methodology flow chart

3.1. BIOMASS FEEDSTOCKS CHARACTERIZATION

Feedstock characterization is the process of analyzing the chemical and physical composition of the biomass substrates. Chemical composition entails the nutrients composition such as

pH, total organic carbon (TOC), total organic nitrogen (TON), and macro & micro minerals. Physical composition comprises of the bulk density, moisture content, and porosity.

Objective; Analyze the carbon, nitrogen, moisture, pH, bulk density and micro and macro composition of feedstocks to facilitate the C / N ratio, humidity and pH calculation for the optimization of feedstock mixing. The feedstocks characterization was performed in partnership with the Kenya Agriculture Livestock Research Organization (KALRO) in Nairobi.

3.1.1. Ethics statement

The collection of the samples was permitted by the owners of the farm in Malidadi area of Kitale at the geographical location of Latitude 01° 08' 39N and Longitude of 034° 59'48E and elevation 1907m. The chicken manure (CM) and the sawdust (SD), were voluntarily provided by a local chicken farmer and saw mill owners respectively. The National Commission for Science, Technology, and Innovation (NACOSTI), issued with research license number NACOSTI/P/18/99643/27086 by the. Therefore, all experimental procedures conformed to the regulations established by the NACOSTI.

3.1.2. Feedstocks sample collection

Samples collected were maize Stover, 56-day matured compost, chicken and cow manure, Sawdust, datura stramonium, green grass, black jack, charcoal, maize cobs and 26-day old compost from the reactor. A kilogram of each, specimen, was collected and packed in airtight

plastic balls. Sampling procedure has was followed as stated by (Marinescu, Volpe, Descrochers, & Roser, 2015; Peters et al., 2003).

3.1.3. Chemical analysis

The objective of the chemical analysis was to determine, Total Organic Carbon (TOC), Total organic Nitrogen (TN), macro & micro minerals (N, P, K, Ca, Mg, Mn, Cu, Fe, and Zn) and pH content. TOC and TN provided the basis to calculate the C/N ratio. In analyzing the feedstock C/N ratio Bajko et al (2018), recommended equations 2.4 and 2.5.

3.1.3.1. Methodology:

Digestion in tubes with H_2SO_4 - salicylic acid - H_2O_2 and selenium. This digestion method was used to analyse N, P, K, Ca, Mg, Mn, Cu, Fe and Zn in the samples (TMECC 4.05 standard) (Peters et al., 2003). Potassium (K) was determined with a flame photometer, phosphorus (P) was determined calorimetrically on spectrophotometer. Total N was measured by distillation followed by titration with 0.1N HCl (Antil, Janssen, & Lantinga, 2009). The determination of; Ca, Mg, Cu, Zn, Mn & Fe was done with Atomic Absorption Spectrophotometer (AAS).

Principle:

The larger part of organic matter in the sample is oxidised by hydrogen peroxide (30% H_2O_2) at relatively low temperature (100 °C). After decomposition of the excess H_2O_2 and evaporation of water the digestion is completed by concentrated sulphuric acid at elevated (330⁰ C) temperature under the influence of Se as a catalyst (Marinescu et al., 2015).

The pH determination

The pH was determined in a 1:10 (w/v) soil/water suspension with FiveGo Portable F2 pH/mV meter, accuracy ± 0.01 , measuring range 0-14 and temperature range 0 to 100 °C and (TMECC 4.11-A (1:10) (Peters et al., 2003).

Total organic carbon: Calorimetric method

All organic carbon in the oven - dry at 40 °C sample was oxidized by acidified dichromate at 150 °C for 30 minutes to ensure complete oxidation. Barium chloride was added to the cool digests. After mixing thoroughly digests are allowed to stand overnight. The carbon concentration was determined on the spectrophotometer at 600 nm (Peters et al., 2003).

3.1.4. Physical Analysis

Moisture Content

The moisture content was determined by drying the sample overnight at 105°C. The percentage moisture is calculated (SM 2540 G standard) using Equation 2.2.6.

Bulk density

Core sampling technique, was used to estimate bulk density. Double cylinder type was the core sampler. The specimen holder was the internal cylinder. The test methods adopted were TMECC 3.01-A under ASTM standards. In the oven, the specimen was dried and then cooled, before being poured into a plastic cylinder before dropping it for 50 taps from a height of 5-30 cm. To assess the specimen's weight, the volume was read, measured, and bulk density calculated by dividing the weight of specimen with its volume.

3.2. LOCATION OF STUDY AREA

Kitale is an agricultural town in northern Rift valley Kenya situated between Mount Elgon and the Cherangany, with a population of 107,806 people by 2009 (UNFPA, 2014). It headquarters the Trans-Nzoia County. The experiment was setup at a location of latitude $01^{\circ} 01'35\text{N}$, Longitude $034^{\circ} 59'23\text{E}$.

3.3. THERMOPHILIC SOLAR DRYING SYSTEM SET-UP

Figure 3.3: shows the schematic drawing of a prototype hybrid solar thermophilic dryer developed as part of the German African Innovation Incentive award with supplementary funding from the Volkswagen Foundation (Muchilwa, 2018). The main parts where, Compost Heat Exchanger (COHE #1), Composting reactor (#2), Thermophilic Dryer (#3) and its accessories, standalone solar heat collector, dryer humidifier, Power supply and Data acquisition and monitoring system (Thermocouple Chart sensor Figure 3.3).

The prototype's pictorial view is as shown in Figure 3.2. Figure 3.2 (a) shows the Square tube frames that formed the core base sections of the COHE and the compost reactor. Figure 3.2(b) shows the compost feedstocks mixture consisting of maize stoves and cobs, cow manure and greens (grass and other organic cuttings). The compost reactor and COHE assembly partially inserted into the mixture of Feedstock is shown in Figure 3.2 (c). Figure 3.2 (d), displays the assembly of the Solar-Thermophilic Hybrid heat collector and drying system.



Figure 3.2:Pictorial view of Compost Reactor/Compost Heat Exchanger Site development.

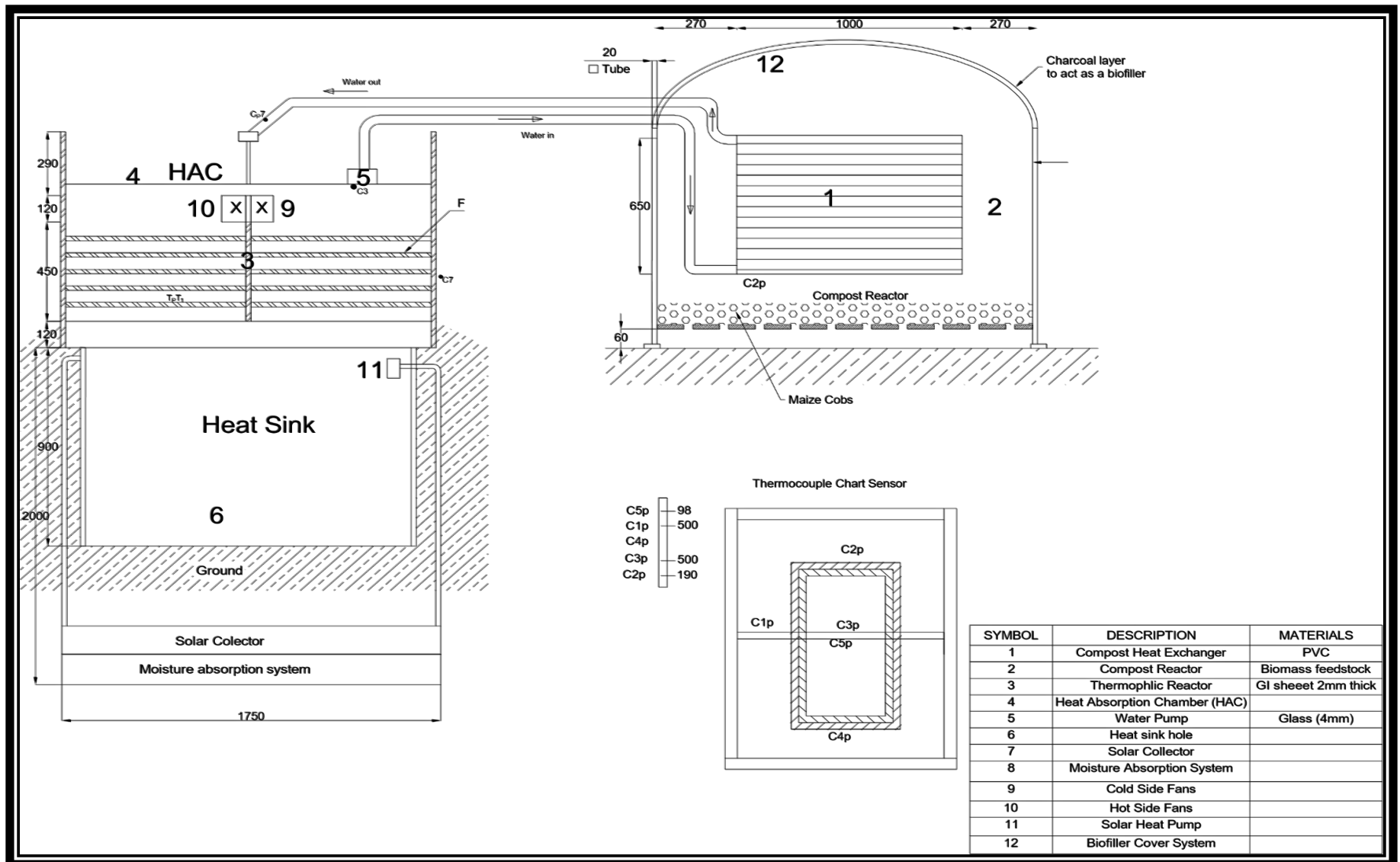


Figure 3.3: Thermophilic dryer general assembly

3.3.1. Thermophilic Dryer Unit Assembly (TDU)

Figure 3.4, shows the layout and installation drawing of the Thermophilic Dryer. The dryer had the following parts: Drying Chamber (housing the drying tray (F), the air fans(X) and the data loggers (TpT) as shown. Heat absorption chamber (HAC) (C), solar heat collector (E), heat sink hole (D) and heat insulation jacket (HIJ). The body was made of a reinforced double wall frame covered with a galvanized iron sheet of 0.003 m thickness. The double wall acted as a thermal insulator.

3.3.1.1. *Drying Chamber*

The length of the drying chamber was 1.5 m including the heat sink (0.9 m hole), 0.75 m wide and 1.8 m high, resulting in a surface area of 10.35 m² and 2.025 m³ volume (9.45 m² available for drying). It had 10 horizontal rails, five on each side to accommodate 0.72 m long and 0.72 m wide drying trays.

Air fans

The hot air circulation was by means of six (6) 90*38mm air fans (D0938C48BYPPA22, 48VDC, 0.14A, NIDEC SERVO, INDONESIA) procured from an online market (Alibaba). The capacity of the fans where 3.6 m³/min maximum flow rate resulting into 21.6m³/min(0.36m³/s) total flow rate with the maximum static pressure of 440pa. Operating temperature range was -40 °C to 57 °C. This fans where installed close to the HAC bottom plate.

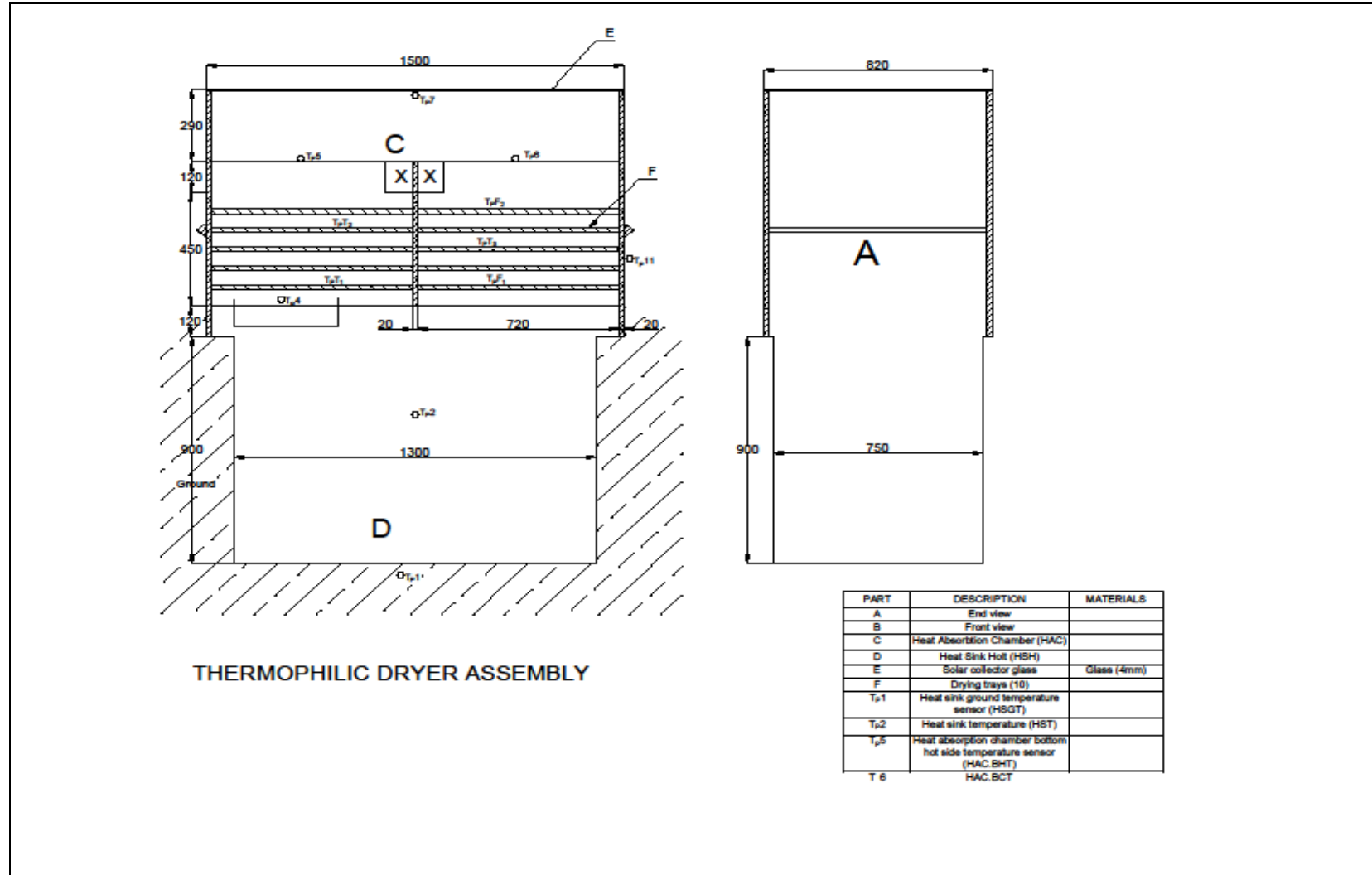


Figure 3.4: Thermophilic dryer assembly

Electrical air heater

An electrical air heater (Clatronic air HL 3378, 220-240V-50Hz, 1000-2000 W), integrated with a fan, was mounted on the rack at 0.002 m from the bottom left side of the thermophilic dryer DC and was used as an energy source for the control test.

Temperature and humidity Data acquisition in the Drying Chamber

In Figure 3.4, the location of the Testo 174 H data loggers (Conrad, Germany) is shown and symbolized by, TpT1, TpT2, TpT3 and TpT4 above the electrical air heater, set to record data at 1-minute intervals, TpF1 and TpF2 where FreeTech data loggers. Online data logging on the PC was accomplished using TpF1 on tray number 1 (bottom right) connected via a 15 m USB cable.

3.3.2. The Heat Absorption chamber (HAC)

The HAC was 1.5m long, 0.76m wide and 0.29m deep translating into, 3.60m² and 0.33m³ area and volume respectively, an area to volume ratio of 10.89:1 (m²:m³). The heat transfer medium used in some experiments was water and filled to 0.21 m in the heat absorption chamber resulting in a volume of 0.24 m³ (240 liters of water (240 kg)). Fabricated from a 0.003 m GI sheet, the HAC was watertight and painted black for better heat absorption.

Temperature and humidity, data acquisition in the HAC

The type K thermocouples ($\pm 0.5^{\circ}\text{C}$, Pico Technology Ltd, UK,) were connected to a 8 channel Pico TC-08 ($\pm 0.2\%$ of reading and $\pm 0.5^{\circ}\text{C}$) data loggers, programmed to record data at 1-minute interval, were used for temperature and relative humidity monitoring. In Figure 3.4, Tp5 and Tp6 symbolize data loggers. Online monitoring was possible through a 15m USB cable connecting the Pico Tc-08 to the PC using picolog software.

3.3.2.1. *Solar heat collector (Top Glass)*

The top part of the thermophilic dryer was a 0.004 m solar collector glass (E), as shown in Figure 3.4. The glass covered the top region of the HAC and by design to cover the exterior dimensions of the HAC with a length of 1.5 m, 0.78 m wide and 0,004 m thick. The grass bought from a local hardware store in Kitale. Three (PTFE) type K thermocouples captured temperature through the Pico TC-08 Data loggers.

3.3.2.2. *Heat sink hole*

The heat sink hole measured 1.3m long, 0.75m wide, and 0.9 m deep and was dug before mounting the thermophilic on top resulting in a volume of 0.88m³. Its main function was to absorb moisture from the hot air from the drying chamber and recycle it back. Two PTFE type K thermocouples and one Testo data logger was used for temperature and Relative humidity data capture indicated by Tp2 and Tp1 in Figure 3.4.

3.3.2.3. *Heat insulating jacket*

The insulating jacket, was made with a length of 1.8 m, a width of 0.85 m and a height of 1.4 m, sown from laminated PVC material and thermal insulation using a 50 mm foam inserted inside to trap heat. It had a top cap to cover the top of the solar collector grass and overlapped with the main body jacket portion. The main function was to reduce heat losses.

3.3.2.4. *Stand-alone solar heat collector*

Was fabricated from the clear PP plastic of 0.003 m thickness and 1.8m long and 1.2m wide, and 0.3 m high with an air porous bottom cloth and connected via the two PVC pipes to the

drying system with a solar powered air pump on the suction side. Operation of this component was restricted to the solar irradiance above 400 W/m^2 . During off solar hours it was disconnected. The air suction only occurred at above 400 W/m^2 irradiance.

3.3.2.5. *Drying chamber temperatures and humidity requirements assumptions*

The desired temperature ranged from 38°C to 55°C at RH of 45% to 75% in the drying chamber. The expected hot water temperature ranged between 47°C to 60°C in the HAC. The expected compost temperature was 65°C . These parameters were used to calculate discrete heat transfer events via conduction through the compost. Steady state flow through radiant tubing, all heat transferred from water in the HAC to the drying chamber (DC), control volume and no water in superheated state, where the assumptions. Table 3.1 indicates the relevant values used in the calculations for designs.

Table 3.1: Designed Parameters

Design Parameters	
Total drying Chamber Area/volume	10.35 m ² /2.025 m ³
Drying Chamber available surface area for drying	9.45 m ²
Drying Chamber Temperature	38°C to 55 °C
HAC Temperature	40°C to 62 °C
Compost Temperature	45°C to 68 °C
Solar Collector Temperature	45 °C to 75 °C
Moisture absorption system capacity	1.4m ²
Drying rates	24 hours
Energy output of the system	150kWh
Heat Absorption Chamber area/volume	3.6m ² /0.33m ³
Thermal Jacket area/volume	1.5m ² /2.2m ³
Dryer Humidifier area/volume	2.2m ² /0.1m ³
Air fan power (Air flow m ³ /s/m ³ /min)	0.36m ³ /s/21.6m ³ /min
Submersible pump calculated flow (L/min, m ³ /min, m ³ /s)	0.075l/min, 0.000075m ³ /min,
HAC water level volume	0.24m ³

3.3.3. Compost Heat Exchanger (COHE)

The COHE, within pile Hydronic type, constructed to extract heat from the compost pile had three main parts as shown in Figure 3.5. The rectangular shaped main frame, the 120 meters low density polyethylene (LDPE) pipe with inner diameter 0.0195m, with a wall thickness

of 0.003 m, 7.4 m² surface area and 0.036 m³ volume, (procured from the local market in Katala) weaved around the frame.

The COHE in this study's design necessitated the winding of the LDPE pipe around its frame then bury the assembly in the center of the compost reactor. This model reduced the negative effects of excessive heat recovery from the compost reactor resulting in microbial inactivity. The aeration level is also preserved due to the vertical placement of COHE in the compost reactor, which decreases the surface area occupied by the pipes (7.4.m² surface area). The disassembly and assembly of COHE was easy and quick, as opposed to laying pipes across the entire compost reactor. The maximum volume of water in the exchanger tube at any given time was 35.7 liters or 35.7 kg of water (equation 3.3).

3.3.3.1. COHE main frame

The frame was 1.2 m long, 1.08 m wide and with 0.65 m breadth and fabricated from 0.002 m square tube. The Low Density Polyethylene (LDPE) hose with a total length of 120 m, was winded onto the frame and secured by means of holding extensions around the frame of 0.07m.

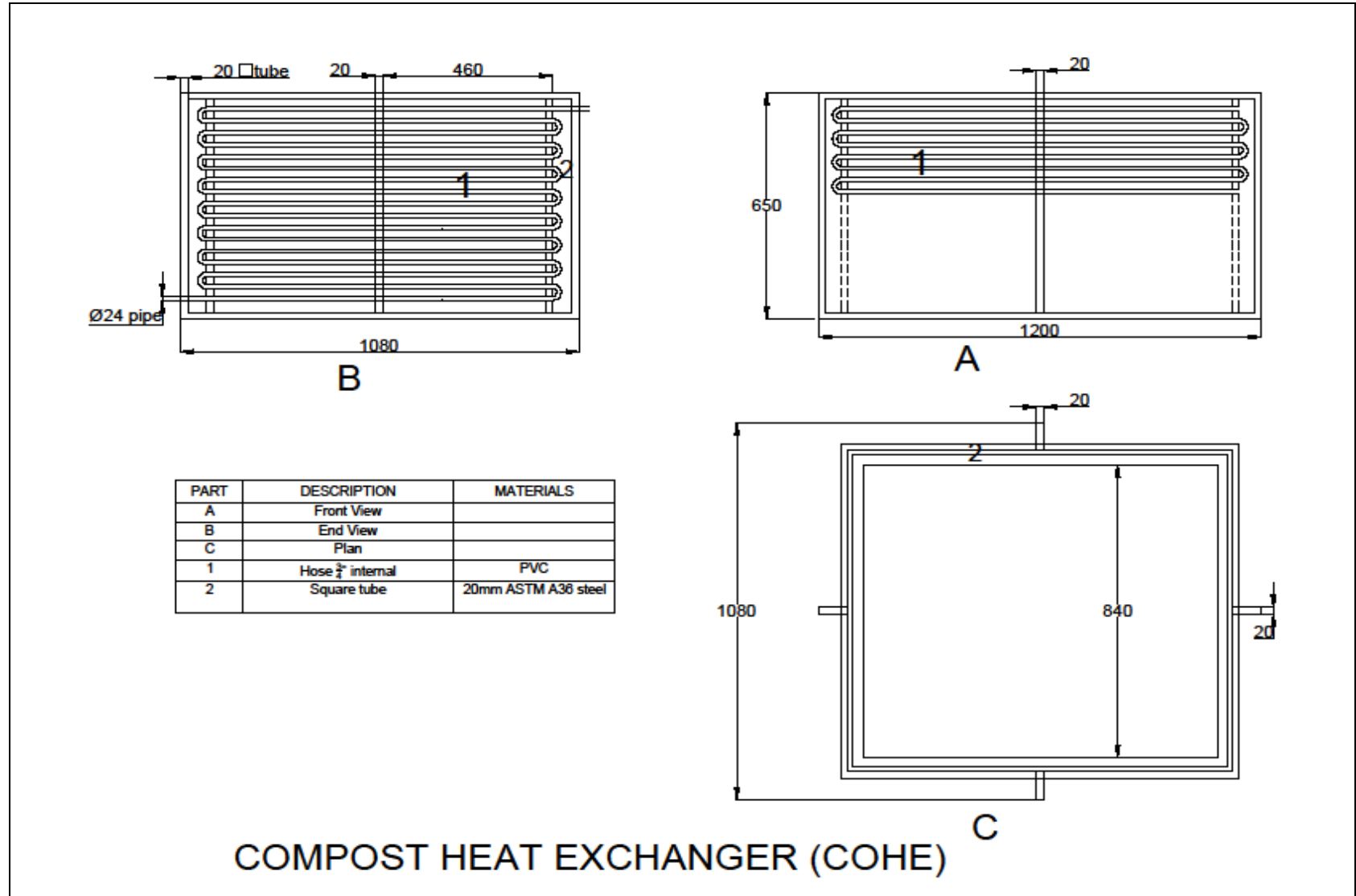


Figure 3.5: Compost heat exchanger (COHE)

3.3.3.2. *Heat transporting medium and circulation*

The heating fluid used in this experiment was water, because of its availability and thermal conductivity properties. The optimum pipe diameter, D , was calculated from the following formula:

$$D = \sqrt{\frac{4(\dot{m}/v)}{\pi}} \quad \text{Equation 3.1}$$

Where, D = Optimum pipe diameter, $\dot{m}$ = Water flow rate, v = water velocity (Irvine et al., 2014). The selected LDPE pipe inner diameter was 0.0195m, with a wall thickness of 0.003m and 120m long, volume of the hose calculated from the following formula:

$$Volume (v) = \pi r^2 L \quad \text{Equation 3.2}$$

Where; v is volume of the COHE hose at any given time, r is radius of the hose used (0.00975m), L is length of the winded hose on the COHE (120m). The water pump discharge indicated the residence water quantity in the COHE at any given instance.

3.3.3.3. *Water circulation*

Two Mini DC12V 3 M micro-motor submersible brushless water pumps of the following specifications; 5W power consumption, 240 L/hr static flow rate, 3 M static lift with 30,000 operating hours of where used to circulate water in a closed loop circuit. The pumps were calibrated and tested and flow indicated, using a bottle with a known capacity and a stop timer (0.025 L/s). Polyethylene (PE) foam insulation material tightly wrapped around the fittings and connections between the compost reactor and the HAC, improved heat insulation.

One thermocouple mounted inside the supply pipe from the pile to the HAC, monitored the temperature of the water.

3.3.3.4. *Summary of the COHE design Parameters (equations)*

Table 3.2 summarizes the design equations used for the COHE parameter determination.

Table 3.2: Summary of design equations

Parameter	Equation used	Reference
Heat Capacity of water (kJ/kg/°C)	$C = \dot{m}C_p$ Equation 3.3	(Irvine et al., 2014)
Volumetric flow (m^3/s)	$\dot{m} = \frac{Q *}{C_p \Delta T}$ Equation 3.4	(Irvine et al., 2014)
Pipe Diameter (m)	$D = \sqrt{\frac{4(\frac{\dot{m}}{\rho})}{\pi}}$	(Earthscan, 2010)
Thermal Energy rate(kj/s)	$E = \dot{m}C_p \Delta T$ Equation 3.5	(Keener, Elwell, Das, & Hansen, 1996)
Mass flow rate ($\frac{kg}{s}$)	$\dot{m} = \frac{mass}{time}$ Equation 3.6	
Mass flow rate (Continuity) (m^3/s)	$\dot{m} = rVA$ Equation 3.7	
Volume of the COHE (m^3)	$\pi r^2 h$ (Equation 3.2)	
Power Extracted (w)	$P = \dot{m}C_p \Delta T$ Equation 3.8	(Bajko et al., 2019)
Length of the Pipe	$L = \frac{Q_h}{Watt/m^2}$ Equation 3.9	

3.3.4. Composting reactor

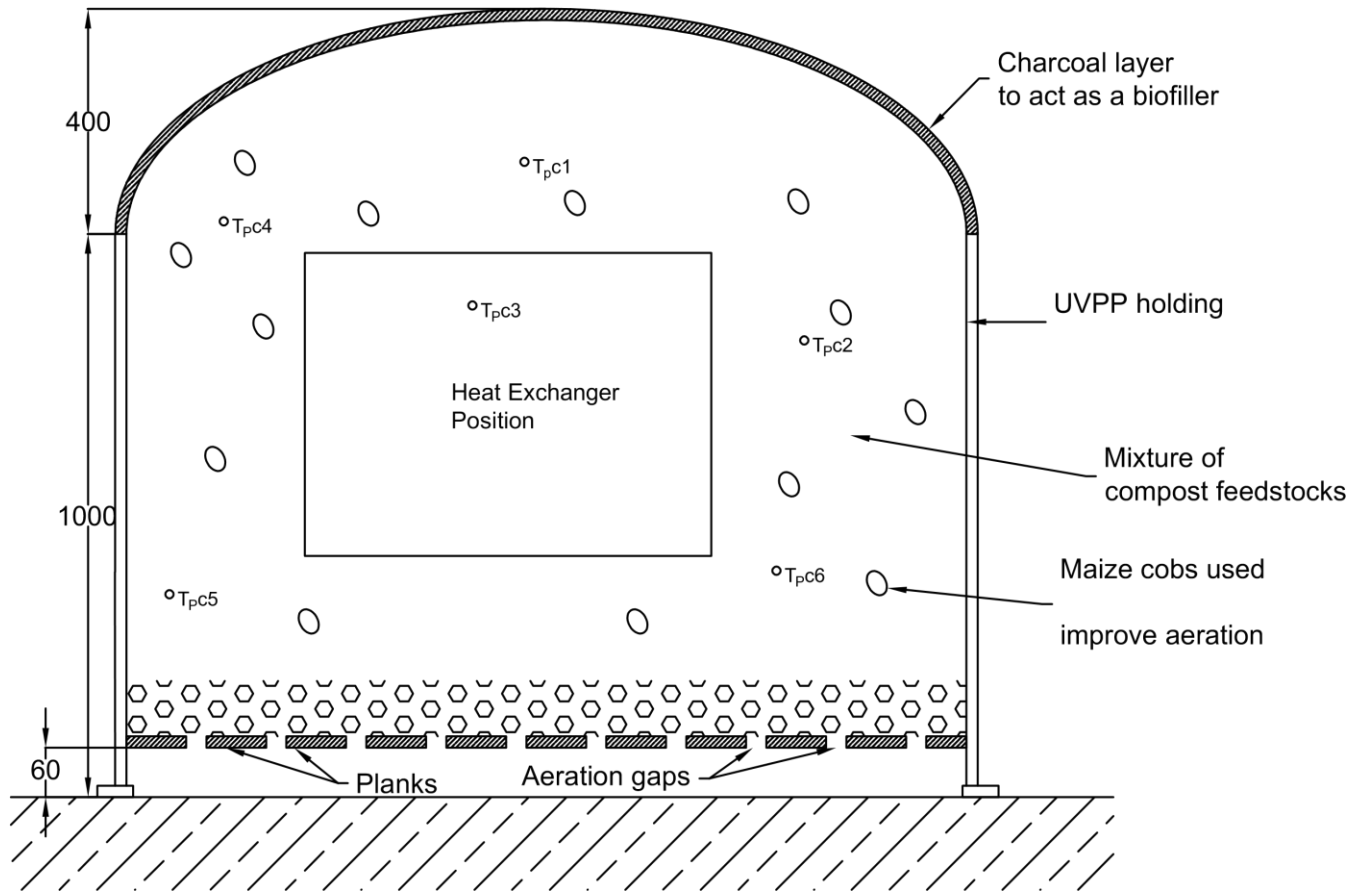


Figure 3.6: Compost Reactor/Compost Heat Exchanger Assembly.

Figure 3.6, outlines, the assembly of the compost reactor and compost heat exchanger (COHE). CHRS design is a complex task and if the system is to work efficiently and generate heat at optimum rates, many factors are considered. (Bajko et al., 2018; Haug, 1993; Rynk et al., 1992). Kitale town (weather, seasons of the year), thermal insulation and composting period, were external conditions considered. The internal factors the model took into account are, the chemical content of feedstocks (C / N, power and micronutrients) .All the above factors are key to created enabling conditions for the microbial operations (Bajko et al.,

2018). The previous quantified and scientifically approved conditions needed to optimize the composting process was attained and followed (María et al., 2018).

Designed as a standalone rectangular, passively aerated, using the gaps left on the base of the pile as shown in Figure 3.6, the compost reactor had a steel reinforced frame outside 0.002 m square steel tubes with the length of 1.84m, width of 1.54 m and height of 1 m, resulting in a volume of 2.83 m³. The surface area was 12.43m² translating into a surface area-to-volume ratio of 4.4 [m²/m³]. The steel frame's outer layer, on all sides, rapped with PP woven fabric to ensure that the material is formed the shape and did not spilling out. Aeration was by means of the chimney effect and a space of 0.06 m left in between the Compost reactor frame and the ground to allow air circulation and allow leachate to drain easily. Figure 3.6 shows the Compost reactor design indicating the position of the COHE and the thermocouples installed at different levels to monitor temperatures from within the pile. The Thermodynamic model of compost reactors for the heat accumulation, was considered using Equation 2.10 (Haug, 1993; Mason & Milke, 2005).

3.3.4.1. *Estimated composition of the compost reactor feedstock and specific heat capacity*

The estimated Specific Heat Capacity (Cp), in the compost reactor used, was determined using the contribution of composition by percentage of each type of feedstock substrate used as shown in Table 3.3.

Table 3.3: Feedstocks specific heat capacities used in this study

Feedstock component	%Composition (mass)	Cp (Kj/kg/k)	Citation	Overall Cp Contribution	Overall Cp
Air	9.09	1.01	(Irvine et al., 2014)	0.09	3.0
Water	57.72	4.18		2.42	
Cow manure	10.47	1.9		(Sutitarnnontr, Hu, Tuller, & Jones, 2014)	
*Green Weeds	7.19	1.63		0.12	
Maize cobs	8.57	1.4		0.12	
Maize stovers	5.94	1.7	(Czajkowski, Wojcieszak, Olek, & Przybył, 2019)	0.01	
Sawdust	1.02	1.5	(S. Wang et al., 2014)	0.02	

*Green weeds constituted: datura stramonium, green grass and black jack.

The average Cp of the feedstock mixture was 3.0 as illustrated in Table 3.3. Specific heat capacities of the green weeds were averaged from the combination of datura stramonium, green grass, and black jack. The temperatures considered are between 25 to 60 °C.

3.3.5. COHE and compost reactor assembly

3.3.5.1. *Aeration*

The matrix used in this study for compost reactor feedstock consisted of cow manure, green weeds, maize stover, carefully combined as a bulking agent with maize cobs. As shown in Figure 3.6 the compost reactor floor had wooden panels with aeration holes. Placing an initial layer of maize cobs on the wooden panels resulted into the creation of air gaps for aeration by chimney effect. After filling well-mixed feedstock layer to 0.3 m level, allowed the COHE

was positioned in place before the filling of the entire area of the compost reactor to 1 m level. A 0.4 m layer poured on top of the compost reactor, saved as a buffer for the shrinkage. Charcoal acted as a bio filter.

3.3.5.2. *Temperature monitoring*

Temperature monitoring was by means of the five SE 000 with 3m cable insulated with Polytetrafluoroethylene (PTFE) type K Pico thermocouples inserted at different levels of the compost reactor hip (Figure 3.2), connected to Pico TC-08 data loggers. They were set to capture data at one-minute interval and to capture data or real time through the PC.

3.3.6. Power supply system and consumption

Two sources of power where designed for the experiment, the 220-230 alternating current voltage (ACV) from the main grid and the backup supply was from the battery, to take up the loads shown in Table 3.4. The backup supply battery was a 12V2000Ah; NP200-12L sealed solar battery procured from Davis and Shirtliff in Kitale, charged by 800 VA 120 charging Scott Power Long Backup Sine Wave UPS, combined charger and inventor, procured from Germany for the previous studies. By means of a 15m power adapter, the backup power supplied the sensor box to the mains at 230 ACV nominal.

Table 3.4: System auxiliary equipment energy demand

Load type	Power (kW)	Voltage (v)
Drying Chamber fans-total load	0.04	48
Control air heater load	0.8	220-240
Submersible water pumps	0.01	12
TOTAL Power (kW)	0.85	

3.4. TESTING AND EVALUATION SETUPS

Testing and evaluation of the system was achieved in phases, from instruments testing, control experiment test (solar and electrical air heater drying chamber heated) in the dry season, solar only in rainy season, thermophilic heated only to drying tests and the drying experiments.

3.4.1. Instruments Testing

These tests were conducted to ensure the performance capabilities of the thermocouples and data loggers. The operational test of the thermocouples and data loggers was achieved by bundling and inserting them together in a sawdust dish while connected to the PC using the Picolog TC-0 data logger. Figure 3.7, displays the devices used to capture data.



(a)-Digital measuring scale (weighing cowpea), (b)-Testo Data Logger (Temperature and Relative Humidity capture), (c)-FreeTec Data logger (Temperature and R.H. capturing),(d)- Pico TC-08 Thermocouple data loggers and SE 000 PTFE) type K Thermocouple (Temperature capturing and data storage).

Figure 3.7: Measuring instruments

3.4.2. Control Test (No-Load –Solar with electrical air heater)

Objective of the experiment: To establish the solar energy contribution to the drying system to maintain the drying chamber temperature and humidity at the nominal drying state. The

sub-assemblies involved and data loggers & thermocouples were arranged as shown Figure 3.3.

The experiment was set up on 17 April 2019, but data recording began on 18 April 2019 at 7:56 am to 19 April 2019 at 7:09 p.m. Upon installing the thermocouples in the HAC and the solar collector glass mounted on top, the gaps between the glass and the HAC upper lips were sealed with silicon. After mounting the electrical air heater at the bottom of the drying chamber the, thermostat was set to come on at 37.5 °C and cut out at 55.5 °C. The heat sink hole was equipped with a ground thermocouple and another one installed at 0.6m from the bottom to capture temperatures.

The electrical fans and the electrical air heater were connected through the backup supply cable powered by 220-230ACV mains supply. All thermocouples were connected to the picolog TC-08-155 and TC-08-319 data loggers set to record at 1 minute interval, connected to the PC inside a data collection room via a 15 m USB cable. By means of the PicoLog 6.1.9 software, data capture and real time monitoring on the PC was achievable. Data was downloaded and evaluated using origin 2018 pro graphing software.

3.4.3. No-Load solar only in the rain season

Objective; to assess the impact of solar drying during the rainy season. Sub-Assemblies involved was the dryer assembly in Figure 3.3. In this experiment the method discussed in Section 3.5.2, but without, the electrical air heating system, was adopted and tests started, on 20 June 2019 to 30 June 2019. The sun was the only source of heat. Using the data loggers

and thermocouples arranged as shown in Figure 3.3 data, was mined, and evaluated, using origin 2018 pro graphing and analysis software.

3.4.4. No-Load test HAC filled with Water and heated by an electrical water heater

Objective: The objective was to establish the optimum temperature of the water in the HAC, required to heat the drying chamber and energy required to maintain humidity 35 % to 75 %.

Sub-Assembly parts considered are as shown in dryer assembly (Figure 3.3) and sectionalized in Figure 3.8. The following equipment and requirements were used in the HAC: three PTFE SE000 temperature profile capture thermocouples, 220-230 ACV electric water heater rated at 300/700W for water heating, 12 DCV/2W air vibrator to carefully mix water to achieve even temperature distribution, water used was from Kitale water utility. Two Testo and two FreeTech data loggers, placed at different points in the drying chamber and the heat sink hole to capture data in real time.

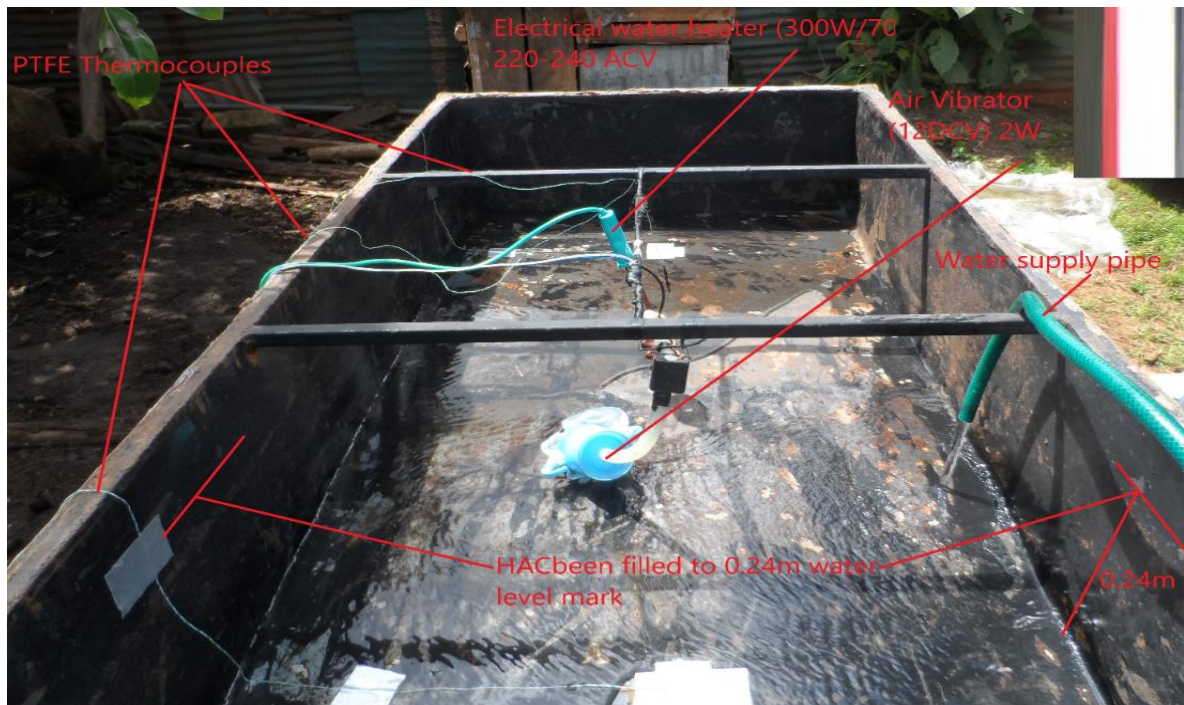


Figure 3.8: HAC during electrically water heated tests.

On 31 May 2019, after testing that the bottom SE 000 PTFE type K Pico thermocouples on the HAC bottom plate were firmly held, the HAC was filled with water at a level of 0.21 m, resulting in a volume of 0.24 m^3 translating into 240 liters of water (240 kg). The experiment began at 08:45 on 31 May 2019, after securely sealing the solar collector, all auxiliary equipment turned on and the doors of the drying chamber shut. The initial water temperature was 27.2°C at an ambient temperature of 18.9°C . On June 2, 2019, the online monitoring system reported that the HAC bottom water temperature was 76.2°C . Electric water heater was turned off at 18:00 on 2 June 2019 and the system was allowed to cool down naturally under close monitoring. On June 4, 2019, the experiment completed when the HAC temperatures cooled down to below 30°C . Data from the Testo and FreeTec data loggers was downloaded and evaluated using the Origin 2018 pro graphing and analysis software to

monitor the effect of the water temperature increase in the HAC on the temperature and humidity of the thermophilic drying chamber systems.

Energy Values

Total average energy consumed by the water heater was 400 watts given by the energy logger and calculated over 45 hours less 2 hours when the power supply was interrupted. Total energy required to heat the 240L of water from 33 to 76.1 °C was calculated using (Equation 3.5), $E = (mC_p\Delta T)/3600$ (E = energy in (kWh), M =Liters of water-240, C_p of water 4.18 and Δ Change of Temperature).

Energy generated in the Drying Chamber was calculated using (Equation 3.5), $E = (mC_p\Delta T)/3600$ (E = energy in (kWh), M = mass of air (2.205 kg) in the DC, C_p of air (1.01) and Δ Change of Temperature). Then the total energy loss was calculated by subtracting the energy used required heat the water to 76.2 °C from the energy used by the electrical water heater.

3.4.5. No-load test-compost reactor HAC water heating and COHE Extraction.

Objective:

The goal was to investigate the energy the compost reactor and compost heat exchanger assembly could generate and extract respectively and its effects on the drying system.

Figure 3.2 (d), shows the compost reactor/COHE assembly connected to the HAC as shown in the designed assembly drawing in Figure 3.3. The outlet of the COHE was the inlet of the HAC and the suction via the submersible pumps discussed was the outlet and inlet for the HAC and COHE respectively. The experiment started on 4th June 2019 to 28th June 2019,

covering the first 24 days of the lifespan of the passively aerated compost reactor and the COHE unit, activities are processed and divided into three main periods, compost only tests, compost heat extraction and extractor performance analysis period and the actual drying tests.

Loading of feedstocks in the compost reactor started on 4 June 2019 (first Day) and completed, on 5 June 2019 (day 2) and temperatures from 6 points of the compost reactor, recorded manually at an interval of 24 hours at 16:50 hrs, using the hand held digital thermometer. Complete online data recording started on 6 June 2019 at 12:57pm. The heat extraction from the COHE and recording started on 6 June 2019 at 13:35, when the average temperatures in the compost reactor were above 65°C. The data loggers were set to record data at 1 minute interval.

3.4.5.1. *Energy values*

Energy generated from the compost reactor

The energy generated from the compost reactor was calculated using the methods described by (Haug, 1993) used by Antizar-Ladislao et al (2010) and Bajko et al (2019), of using a standard heat flow into a substance at constant pressure. Keener et al (1996) is one of the researchers who utilized this method too, applying equation 3.10 for energy balance analysis.

$$Q = mC_p\Delta T \quad \text{Equation 3.10}$$

Where; Q is heat energy stored in the compost (kJ/kg), M is compost mass (kg), C_p = overall specific heat capacity (3.0 kJ/kg/°C) of the ingredients in the feedstocks of the compost reactor at a constant pressure and ΔT is the change in Temperature. Heat energy values, were

worked out at each 30 minutes time step using the estimated feedstock material concentration and standard specific heat capacity values worked out in Table 3.5.

Energy extracted by the COHE and its coefficient of performance (COP)

The energy extracted by the COHE was calculated modifying equation 3.8:

$$ql = \dot{m}C_p(T_{COHE\ out} - T_{HAC\ out})Xt\ (kJ)$$

ql is energy leaving the COHE system in kJ, $\dot{m}$ is the mass flowrate of water, C_p is the specific heat capacity of water (4.18 kJ/kg/°C taking properties of water at 30 °C). The temperature changes were, ($T_{COHE\ out}$) denoting the temperature of the water from the COHE to the HAC and ($T_{HAC\ out}$) the temperature of the water from the HAC pumped back to the COHE, t is the time in hours when the water circulating pump was on. The thermal flow performance and the Coefficient of performance (COP) was analyzed using Equation 2.8 (Allen & Chambers, 2009).

Temperatures were group up in 30 minutes intervals and energy values calculated using the OriginPro 2018 graphing & analysis software.

3.5. SOLAR/THERMOPHILIC HYBRID SYSTEM PERFORMANCE INDICATOR

3.5.1. Drying Test- Compost reactor generated heat (COHE Extracted)

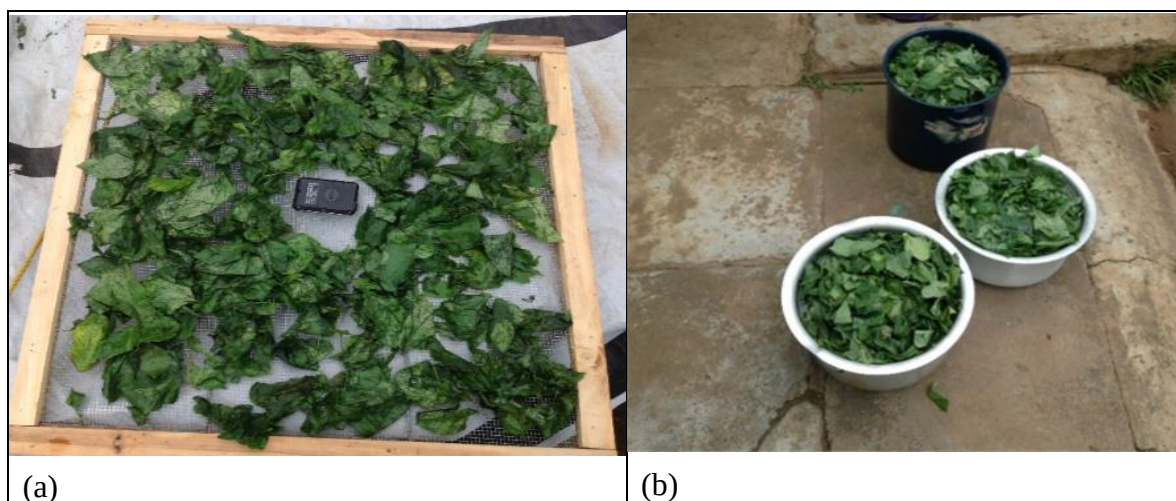
On 18 June 2019, locally grown cowpea leaves, Kunde in Kiswahili and scientifically known as *Vigna Unguiculata*, plucked from a farm in Malidada in Kitale and immediately prepared

for drying to avoid changes in color, taste, texture, and nutrients. Vegetables were cleaned, scratched & old pieces removed using running water to wash well before draining and blanching using a microwave for 5 minutes at 40 degrees Celsius. In Figure 3.10, the Cowpea in pots and on the drying trays are presented. The vegetables were, weighed, and placed on the weighed drying trays. Table 3.5, illustrates the weights of the vegetables on each tray from T1H to T5H and T1C to T5C.

Table 3.5: Cowpea vegetables loaded on trays

Tray Number on (H.S)	Weight Wb (grams)	Tray number on C.S.	Weight Wb(grams)
T1H	2102	T1C	2021
T2H	1760	T2C	1851
T3H	1543	T3C	2322
T4H	1268	T4C	2692
T5H	1037	T5C	2247
TOTALS (TH)	7710	TOTALS(TC)	11133

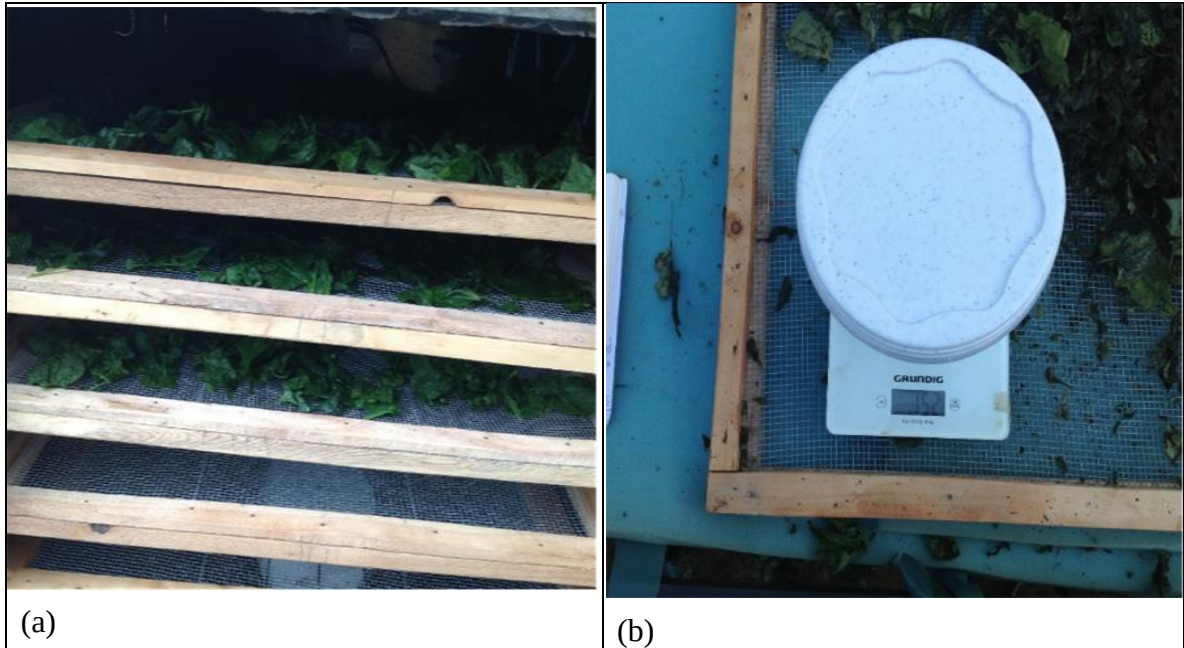
**TH are trays on the left side of the dryer hosting the electrical heater (Hot side) and *TC are trays on the right side facing the doors.*



(a)-Cowpea leaves on the tray and a data logger in place (b)-Blanched cowpea leaves in pots

Figure 3.9: Blanched vegetables.

All data loggers were located as shown in Figure 3.3. With loaded trays inserted into the drying chamber, doors closed, the fans turned on, the drying began at 16:14 on 18 June 2019. The cycle continued undisturbed and constantly monitored on the PC via the data loggers, until the relative humidity of the DC on the PC was constantly at 40%. At 14:33 on 19 June 2019, fans were shut off and the drying chamber opened. Weighing of vegetables using the Grundig digital scale with an accuracy of ± 0.01 tray was done and weights recorded in the logbook against the initial weights. The data loggers, downloaded and data analyzed using the Origin Pro 2018 graphing and analysis software. Figure 3.11 shows the weighing scale and loaded trays in the drying chamber are shown.



(a)-Loaded trays inside the dryer, (b)-Weighing vegetables after drying

Figure 3.10: Loaded trays inside the dryer(L) and vegetables been weighed after drying (R).

3.5.2. Calculations

The adopted initial moisture content in this study was 85 %. Previous studies, in Kenya and abroad, have indicated a moisture content of 78 % to 88 % and total solids between 11.26 +/- 0.26 to 14.29 +/- 0.26 (Gómez, 2003; Mutali & Mbugu, 2015).

3.5.3. Energy calculations

3.5.3.1. Dryer Energy consumption Equations

The energy consumption of the dryer and what was required for the drying of the (Cowpea (Kunde) vegetables was calculated using equation 3.11.

$$E_t = Av\rho_a C_a \Delta T D_t \quad \text{Equation 3.11}$$

Where; E_t represents total energy in each drying period in kJ. A is the area of the cross section of the drying chamber (m^2), ρ_a is the density of the air in kg/m^3 . ΔT is the temperature differences, in $^{\circ}\text{C}$. D_t represent the total time for drying the samples in hours(Hr) and C_a is specific heat capacity of air ($\text{kJ}/\text{kg}/^{\circ}\text{C}$); while v is the air velocity in m/s .

3.5.3.2. *Energy responsible for drying 1g of fresh vegetables*

The energy responsible for drying 1g of fresh vegetables was obtainable using equation 3.12.

$$E_m = \frac{E_t}{W_o} \quad \text{Equation 3.12}$$

where, $E_{m(\text{Kg or g})}$ is the specific energy required, kJ/g or kJ/kg ; W_o is the starting mass of the sample in g or kg and E_t is the total energy generated in the drying period (Holman, 2012; Irvine et al., 2014; 2007; Mutali & Mbugu, 2015).

Heat Energy, Q required for drying the vegetables

The Energy Q required to dry the crop at optimum temperature was given by:

$$\begin{aligned} Q(E_t) &= E_1 + E_2 + \text{Loss} \\ Q(E_t) &= MwL + M_c C_{pc}(T_b - T_a) + \text{Loss} \end{aligned} \quad \text{Equation 3.13}$$

Where, $Q = E_t$ is the total Psychometric energy required to dry the Cowpea, E_1 is Energy required to raise the Cowpea temperature up to drying Air Temperature in the sensible heat, E_2 is energy required to evaporate the moisture (Latent heat of Vaporization for removal of moisture) and the rest of the energy not accounted for in E_1 and E_2 is lost energy. L is latent

heat of vaporization of water, M_w is the weight of the moisture to be removed, M_c is mass of product Cowpea, C_{pc} is the specific heat capacity of Cowpea, T_a is ambient temperature and T_b is the drying chamber Temperature ($^{\circ}\text{C}$). (Behera & Das, 2019; Holman, 2012; Irvine et al., 2014; Koyuncu et al., 2007; Mutali & Mbugu, 2015).

3.5.3.3. *Energy lost*

Energy lost was calculated by:

$$\text{Lost Energy} = Q(E_t) - M_w L + M_c C_{pc}(T_b - T_a) \text{ (kJ) from equation 3.13.}$$

3.5.3.4. *Moisture content (M.C.) wet weight basis (w.w) and dry basis (db).*

The formula below, applied during the moisture content wet basis calculations:

$$\text{Drying MC (\%)} = \left(\frac{M_i - M_f}{M_i} \right) \times 100\% \text{ wet basis} \quad \text{Equation 3.14}$$

M_i = mass of sample before drying and, M_f = mass of sample after drying (Fudholi et al., 2011).

3.5.3.5. *Moisture content dry basis:*

$$\text{M.C. (dry basis) } Y = \frac{w(t) - d}{d} \quad \text{Equation 3.15}$$

Where; $W(t)$ = mass of weight material at instant t , d = mass of dry materials (Twidell & Weir, 2006).

3.5.3.6. *Average drying rate*

The average drying rate, M_d , then determined by dividing the amount of mass of moisture by the time it took to remove the moisture using the following equation;

$$\text{Average drying rate (Mdr)} = \frac{m_w}{t_d} \quad \text{Equation 3.16}$$

Where,

M_{dr} = average drying rate, kg/hr, m_w = evaporated water mass (Kg), t_d = total time spent for drying (hr).

3.5.3.7. *The drying process efficiency*

The drying efficiency, was calculated using the following Equation;

$$\eta_{\text{syst}} = \frac{(M_w \times L_v) + (M_a \times C_{pa} \times \Delta T)}{Q_a} \quad \text{Equation 3.17}$$

Where;

Q_a = Total energy supplied to the dryer, M_w = mass of evaporated H₂O, L_v = latent heat of vaporization, M_a = mass of the dried Cowpea (Kunde), C_{pa} = specific heat capacity of the (Cowpea) kunde, ΔT = change in temperature of the chamber (Amer, Hossain, & Gottschalk, 2010; Behera & Das, 2019; Garden-Robinson, 2017; Twidell & Weir, 2006).

3.5.3.8. *Dryer Efficiency*

The follow applied for calculating the Dryer efficiency:

$$\eta_d = \frac{ML}{(Et)} \quad \text{Equation 3.18}$$

Where; L = latent heat of vaporization of water, M is the total mass of the crop, E_t is the total energy generated in the drying chamber during the period of drying (Hossain et al., 2009; Twidell & Weir, 2006).

3.5.3.9. *Thermal/Energy Efficiency*

The energy efficiency (η) was calculated by relating the energy used for moisture evaporation at the vegetables (Kunde) feed temperature (E_{EV}) to the total energy supplied to the dryer (E_t) (Kudra, 2012). The equation is presented as;

$$\eta = \frac{E_{ev}}{E_t} \quad \text{Equation 3.19}$$

3.5.4. **Thermal Efficiency**

Thermal efficiency (η_t) was calculated according (Adegbite et al., 2019; Kudra, 2012; Mujumdar, 2015); based on the inlet air temperature (T_{in}), the out let air temperature (T_{out}) and the ambient temperature (T_{amb}) coordinated in the following Equation.

$$\eta_T = \frac{T_{in} - T_{out}}{T_{in} - T_{amb}} \quad \text{Equation 3.20}$$

3.6. MATERIALS EQUIPMENT AND TOOLS FOR THE STUDY

Table 3.6 and 3.7 shows the materials used for fabrication & testing and the sensors & data loggers used for data capturing and storage respectively. The accuracy and quantities are stated.

Table 3.6: Materials & equipment used for fabrication and testing

Material	Quantity	Specifications
COMPOST REACTOR		
Welded frame	1	1.84 m x 1.54 m x 1 m
Wooden panels	5	0.2 m x 1.5 m
PVC sheet	1	1.5 m x 10 m
PE coils	1	20 m
Compost mixture	1350 (kg)	Farm wastes & weeds
COMPOST HEAT EXCHANGER (COHE)		
Welded frame	1	1.08 m x 1.2 m x 0.65 m
Submersible pumps	2	Mini DC12v 3 m micro-motor
LDPE pipe	1	0.019 m(I.Dia), 120 m(Length)
Pipe connectors	6	0.018 m
Clipping wire 10m	1	20 m
THERMOPHILIC DRYER		
Welded double wall housing	1	1.5 m x 0.98 m x 0.82 m
Wooden trays	10	0.72 m x 0.8 m
Air fans	6	90*38 mm (D0938C48BYPPA22 48VDC)
Air heater	1	(Clatronic HL 1000w)
Sola collector glass	1	1.5 m x 0.78 m (1.17 m ²)
Cowpea vegetables (Kunde Kg)	20 (kg)	Fresh from the garden

Table 3.7: Data logging equipment and sensors

Sensors	Quantity	Instrumentation	Accuracy
Testo 174H data logger	5	RH/Temp	$\pm 0.5\text{ }^{\circ}\text{C}/\pm 3\text{ \% RH}$
FreeTec data loggers	2	RH/Temp	$\pm 0.8\text{ }^{\circ}\text{C}/\pm 4\text{ \% RH}$
Pico TC-08 thermocouple data loggers	2	Temp	$\pm 0.2\text{ \%}$ of the reading and $\pm 0.5\text{ }^{\circ}\text{C}$
SE000 PTFE type k thermocouples	14	Temp	$\pm 1.5\text{ }^{\circ}\text{C}$
Digital Grundig Scale	1	weight	1 gram
CEM DT 1307 Solar power meter	1	Solar insolation	$\pm 10\text{ W/m}^2$

3.7. STATISTICAL ANALYSIS

The statistical analysis of the data sets extracted from various test protocols, was achieved by using Origin Pro 2018 graphing and analysis software. The test results discussed in this section are; Instruments operational tests, No load tests involving control test (Solar and Electrical Air Heater), No load test (Solar only in rainy season), No load test- HAC water heated by an electrical water heater and the load test by drying cowpea vegetables.

The generated temperature regimes, made it possible to measure the temperature and relative humidity variations in the drying chamber, averaged over experimental times under various heating sources. The source of heating in the control trial was solar and an electrical heater fitted in the drying chamber. No-load tests heat sources were; solar only in the rainy season, water heated by an electrical heater and compost reactor. Energy generation within the compost was calculated using compost temperature data over a month long trial (Allen &

Chambers, 2009). The performance coefficient of the COHE was determined during the experimental trial period by the ratio of the energy extracted from the compost divided (over) the pumping energy used to circulate the heated water.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 FEEDSTOCK CHARACTERIZATION

The results for the characterization of the feedstocks carried out at KALRO Appendix A, were used to calculate the overall moisture content using Equation 2.6 and C/N ratio using equation 2.4. The pH was calculated by considering each substrate contribution to the mixing matrix by mass percentage.

4.1.1. Physical analysis

In this analysis, the total weight used in the compost reactor for the feedstock mixture was 1350.2 kg wb, with an average moisture content of 57.7% (779.1 kg). On dry basis, total weight was 571.1 kg. Table 4.1 indicates the weight contribution of each feedstock used in kg.wb, moisture content (percent) and weight (kg), db weight (kg) and percentage contribution on dry basis and (Equation 2.6) applied to calculate moisture content.

Table 4.1: Feedstocks composition

Material	Weight (kg)wb	Moisture content (%)	Moisture (kg)	Weight (kg)db	%Composition (db)
Cow manure	180.7	21.8	39.39	141.31	10.47
Greens	804	87.9	706.72	97.28	7.20
Cobs	134	13.6	18.22	115.78	8.58
Maize stovers	91	11.9	10.83	80.17	5.92
Sawdust	17.7	22.1	3.91	13.79	1.02
Air	122.8			122.8	9.09
Moisture					57.7
Total	1350.2		779.07	571.1	100

Air composition was taken to be at an average of 9.1% of the total weight as recommended by (Adams, 2005).

4.1.2. Chemical Analysis

Table 4.2 and 4.3, presents the Total Carbon Content (TCC) dry basis and Total Nitrogen Contents (TNC) dry basis, of the feedstocks used in this study, respectively. After the determination of the TCC and TNC, the C/N ratio was calculated using (Equation 2.4).

Total Organic carbon analysis

Table 4.2, presents the carbon contents in the feedstocks used in this study. By considering the percentage, contribution of each substrate based on dry basis weight (448.33 kg), the total carbon content of the mixture was calculated.

Table 4.2: Carbon content in substrates

Feedstock Type	Weight db(kg)	Carbon Content (%)	Carbon (kg)	% Composition
Cow manure	141.31	20.6	4.24	0.95
Greens	97.28	35.63	34.66	7.73
Cobs	115.78	37.3	43.19	9.63
Maize stovers	80.17	49	39.28	8.76
Sawdust	13.79	46.5	6.41	1.44
TOTAL	448.33		127.78	28.5

From the total 448.33 kg (db) weight used in this study, excluding air, Total Carbon Content calculated was 28.5 percent.

Total Nitrogen

Figure 4.3 indicates the total nitrogen present in the substrates tested at KALRO. The contribution of the individual substrate by percentage dry basis mass, determined the Total Nitrogen content of the setup.

Table 4.3: Nitrogen content in the substrates

Materials	Weight db(kg)	Nitrogen Content (%)	Nitrogen (kg)	% Composition
Cow manure	141.31	1.28	1.81	0.40
Greens	97.28	1.71	1.66	0.37
Cobs	115.78	0.47	0.54	0.12
Maize stovers	80.17	0.47	0.38	0.09
Sawdust	13.79	0.47	0.06	0.01
	448.33		4.46	0.99

The Total Nitrogen content was 0.99 %.

C/N Ratio

The C/N ratio calculated was of 28.8:1 using equation 2.5. This is in conformity with the British Columbia ministry of agriculture and food's recommendation of the C/N ratios between 25:1 to 40:1 (BCMAF, 1998). The C/N ratio of 30:1 was applied in other research works to achieve the efficient composting process (Adams, 2005; Bajko et al., 2018) A C/N ratio between 20:1 to 32:1 has been recommended (Epstein, 2011).

pH Calculations

Table 4.4 indicates the pH content of each substratum. The average pH, was determined by percentage measurement of the pH present in each substratum and then added. The mean pH of the mixture was 6.8. This is in conformity to the recommended pH between 6.5 to 7.5 (BCMAF, 1998). Bajko et al (2018) and Allen & Chambers (2009) reported the pH of 6.9 applied in the experiments of Fitzgerald (2009), (Allen & Chambers, 2009; Bajko et al., 2018).

Table 4.4: pH content in substrates

Materials	Weight (kg)	%Contribution	pH	pH-Contribution
Greens	804.02	65.5	5.9	3.9
cobs	134	10.9	8.6	0.94
Maize stovers	91	7.4	7.9	0.58
Cow manure	180.73	14.7	9.1	1.34
Sawdust	17.7	1.4	6.4	0.1
TOTAL	1227.45	100		6.8

Micro and macro Minerals

The composition of key elements in the feedstocks is as shown in appendix A.

4.1.3. Feedstock Characterization results

Table 4.5, shows the final chemical and physical composition of the feedstocks used in the study. The findings are consistent with previous researchers ' proposed optimum compost

feedstock mixtures. All suggested C/N ratio of 20:1 to 30:1, moisture content 50-60%, pH 5.5 to 8.0. Therefore, the mixture was at the optimum composition for the efficient composting process (Bajko et al., 2018; Epstein, 2011; Haug, 1993).

Table 4.5: Summary of characterization results of the feedstocks

Parameter	Quantity
Moisture	57.7 %
TOC	28.5 % db
TON	0.99 % db
pH	6.8
C/N	28.8:1

4.2 DESIGN PARAMETERS

In this section, the design parameters used in this study, are presented and discussed in table form.

4.2.1 Compost reactor feedstock mixing ratios

The compost mixture consisted of the following highlighted parameters and quantities in Table 4.6.

Table 4.6: Feedstock parameters

Design parameters	Units
Total Feedstock weight (kg) wb	1350.2 kg
Moisture content (%)	57.7 %
Moisture content (kg)	779.07 kg
Total weight (db)	448.33 kg
C/N ratio	28.8:1
pH	6.8
Average Specific heat capacity (Cp) kJ/kg/k	3.0
Air required (Total kg)	122.8

4.2.1.1 Estimated specific heat capacity (Cp) of the Compost feedstocks Matrix

The mean specific heat capacity of the feedstock mixture used in the experiment was 3.03 kJ/kg/°C as indicated in Table 4.7 and assumed to be at constant pressure. This method has been reported during the investigation of the potential of harnessing heat from the composting facility at Deerdykes in Scotland (Irvine et al., 2014). Allen & Chambers (2009), achieved calculating energy extracted from the compost using the Cp this method. Therefore, the system and methods used in this study conforms to the proven research work.

Table 4.7: Estimated material and Cp composition for this research

Feedstock Composition	%composition	Cp(kJ/kg/k)	Overall contribution	Compost Overall Cp
Air	9.1	1.01	0.092	3.03
Water	57.7	4.18	2.42	
Cow Manure	10.4	1.76	0.18	
Maize cobs	8.6	1.4	0.12	
Maize stovers	5.9	1.4	0.08	
Sawdust	1.0	1.4	0.01	

4.2.2 Compost heat exchanger (COHE)

The working parameters of the COHE are as shown in Table 4.8. The thermal conductor used in this study was water. Allen & Chamber reported the utilization of a water /glycol mixture for heat conduction. Water/glycol mixing was done to improve the thermal conductivity of water (Allen & Chambers, 2009). Bajko et al (2019) achieved a volumetric flow rate of 4.6 L/min ($7.66 \times 10^{-5} \text{ m}^3/\text{s}$), realizing ΔT of 6.01, 4.88 and 4.33 °C, using the condenser type heat exchanger. (Bajko et al., 2019). The temperature of 35°C maximum and 5 °C mean ΔT with a 0.4 standard deviation was achieved in this research. (Refer to Figure 4.15). The flow rate of 1.5 L/min through the COHE, was achieved, in this study lower than Bajko et al (2019) (4.6 L/min) reported

Table 4.8: COHE system parameters

Parameter	Values	Equation number
Mass flow rate of the fluid (H ₂ O)	0.025 kg/s	Equation 3.6
Heat Capacity of water	104.5 J/°C	Equation 3.3
Volumetric flow	0.000025 m ³ /s	Equation 3.4
Thermal Energy rate	1.1 kJ/s	Equation 3.5
Volume of the COHE	0.036 m ³	Equation 3.2
Length of Pipe	120 m	
Power Extracted	202 kwh	Equation 3.8
Thermal conductor	Water	

Irvine et al. (2014), reported a 3 L/min heat exchanger, achieved heated water temperatures between 47.3 and 50 °C and was used to satisfy underfloor heating hot water demands (Irvine et al., 2014). HAC water temperatures ranging from 48 to 58 °C, were reached in this study, making the analysis comparable and adaptive to research. Figure 4.1, shows the COHE.

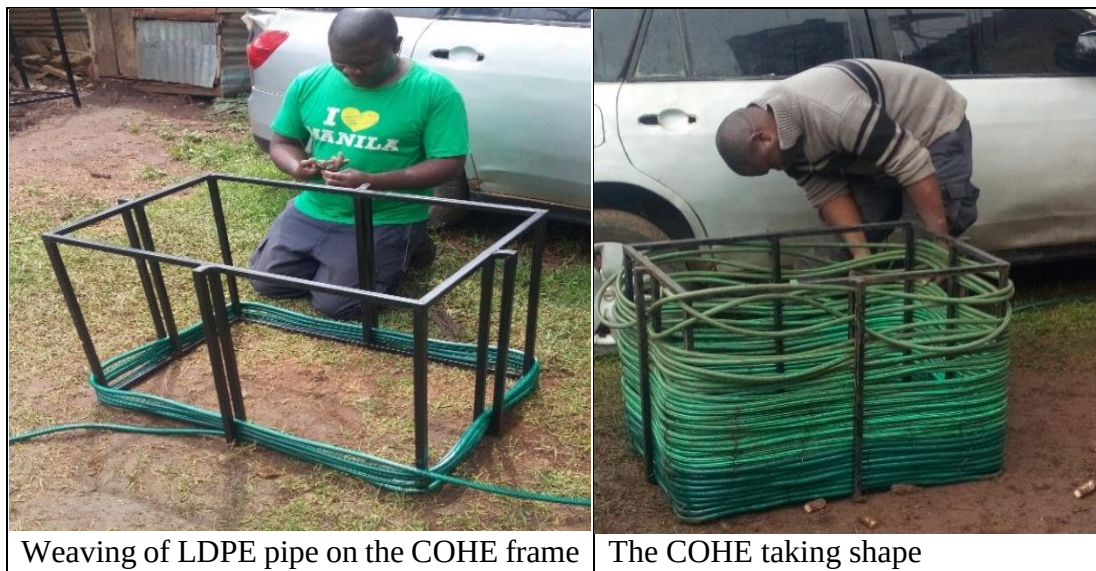


Figure 4.1: Construction of the COHE

4.2.3 Solar-Thermophilic dryer

Table 4.9, highlights the key thermophilic dryer design parameters achieved that were important for energy calculations..

Table 4.9: System parameters for the Thermophilic Dryer

Design Parameters	
Total drying Chamber Area/volume (m^2/m^3)	10.35/2.025
Drying Chamber available surface area for drying (m^2)	9.45
Drying Chamber Temperature achieved ($^{\circ}\text{C}$)	38 to 55
Solar collector area (m^2)	1.17
Solar Collector Temperature achieved ($^{\circ}\text{C}$)	45 to 75
Moisture absorption system capacity (m^2)	1.4
Drying rates achieved (hr)	18
Air fan capacity (Air flow m^3/s , m^3/min)	0.36/21.6
DC Air velocity (m/s)	16.5
Submersible pump calculated flow (L/min , m^3/min , m^3/s , kg/s)	0.075/0.000075/0.025
Number of trays	10

The total area of the drying chamber (DC) available for drying was 9.45 m^2 . The average air velocity was 16.5 m/s .

4.2.4 Weather Condition of Kitale in June

Table 4.10, is a summary and description of Kitale's geographical conditions shown in Figure 4.2 to Figure 4.7. The precipitation, maximum & minimum ambient temperatures for June 2019 are shown in Figure 4.2. June and July were months of 5.4 and 5.1 Incident Shortwave Solar Energy (ISSE) respectively with a minimum monthly mean as indicated in Figure 4.7. Lowest sunshine hours, are reported, in July 6.2 hours per day (Figure 4.5). Intentionally, the research went on during this period to optimize findings with a recorded R.H of 81 %.

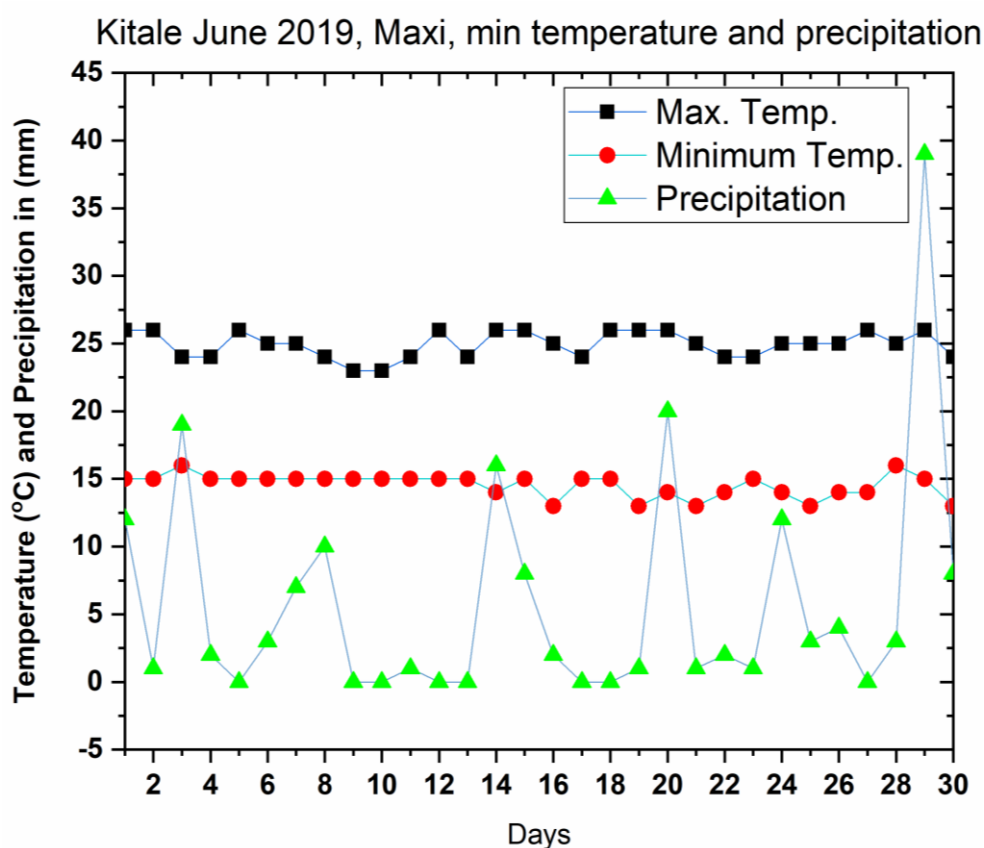


Figure 4.2: Maximum, minimum temperature and precipitation of Kitale (June 2019).

The mean maximum temperature of 25.1 °C, mean minimum temperature of 14.9 °C and 11.4 mm rainfall, weather conditions characterized the month of November in Kitale, as shown in Figure 4.2. Kitale experienced a Maximum and minimum monthly average temperature of 25.1 °C and 12.5 °C in 2018 respectively.

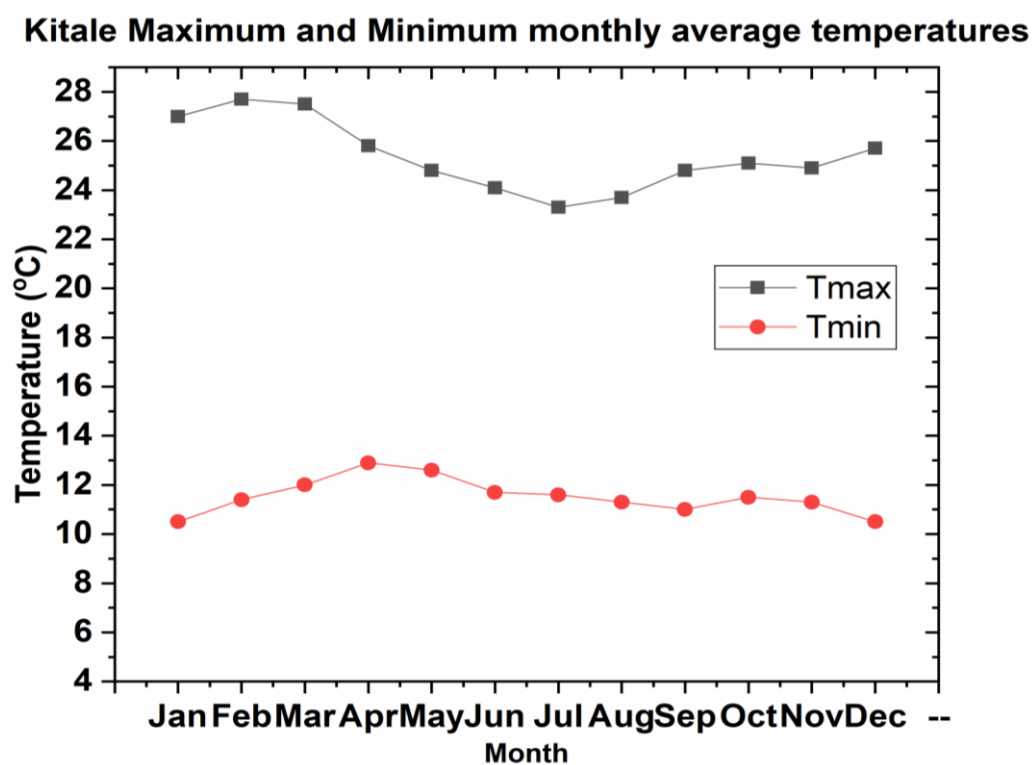


Figure 4.3: Kitale Maximum and minimum monthly average temperature.

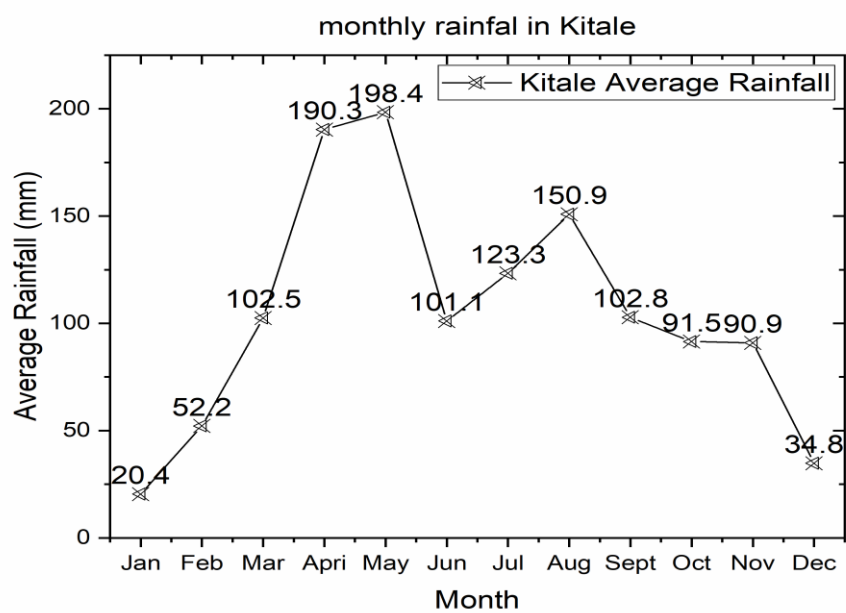


Figure 4.4: Kitale monthly average rainfall (2019)

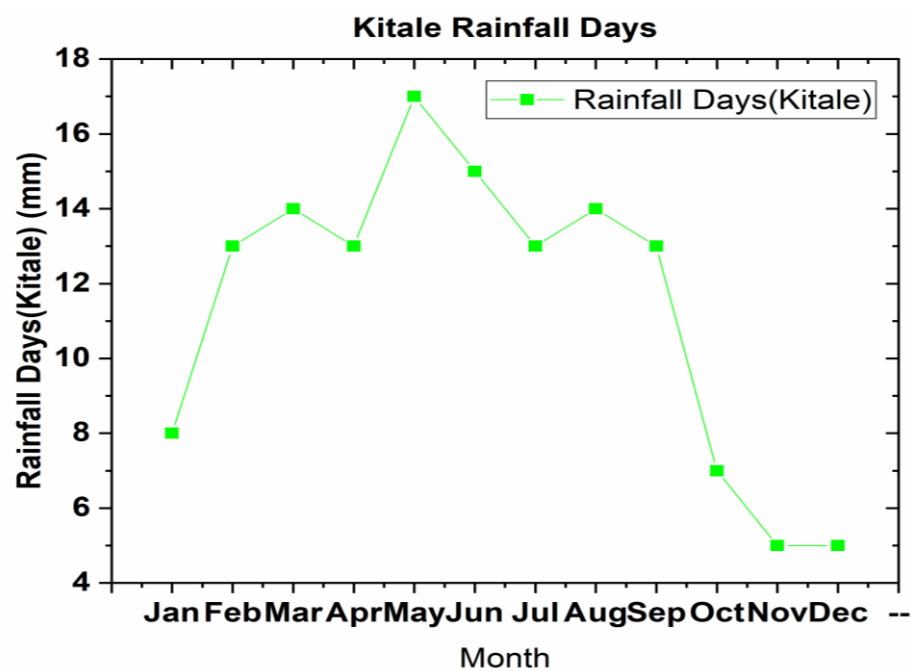


Figure 4.5: Kitale monthly rainfall days (2019)

The highest and lowest average rainfall in Kitale year ending 2018, was experienced in May and January respectively, as depicted by Figure 4.4. Figure 4.5 shows that May registered 17 rainfall days as compared to the lowest in December.

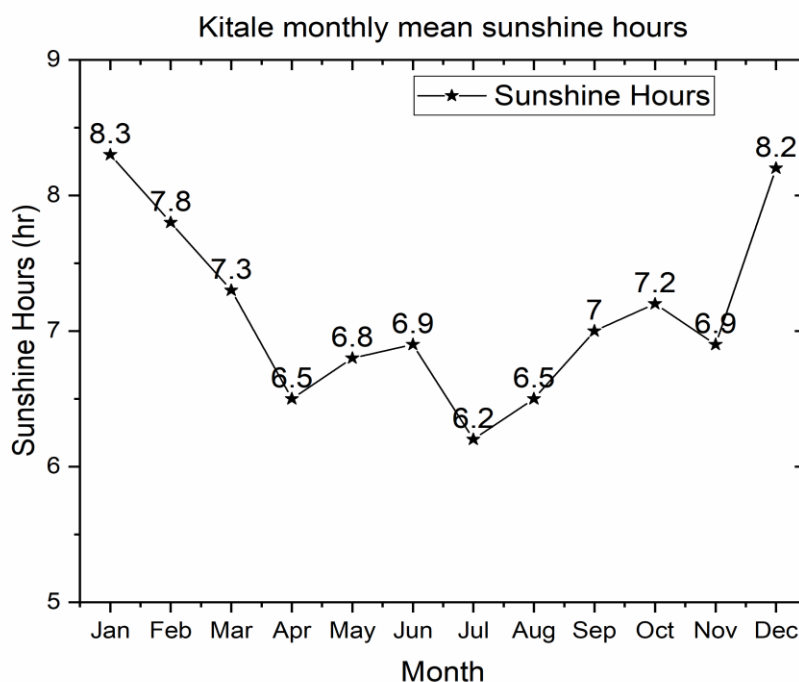


Figure 4.6: Kitale Monthly mean sunshine hours

In the year ending 2018, the mean minimum sunshine hours as shown in Figure 4.6, was in July with 6.2. December registered 8.2 sunshine hours. This translated into 5.1 kWh minimum mean shortwave solar energy and 7.5 kWh maximum mean shortwave solar energy for July and February, respectively (Figure 4.7).

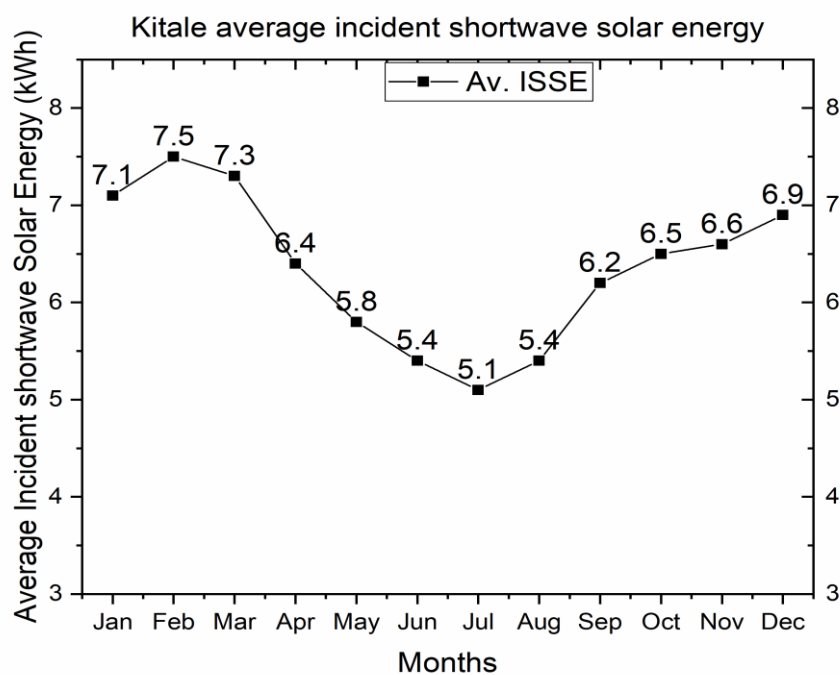


Figure 4.7: Kitale average incident shortwave Solar Energy (kWh).

Table 4.10: Average monthly geographical conditions of Kitale depicted from Fig 4.2 to Fig 4.7.

Climatic data name	Quantity and units
Daily global radiation $\dot{H}$	19.7 MJ/(m ² -day)
Ratio of the diffuse radiation $\dot{H}_d$ to global radiation $\dot{H}$	0.52
Ambient Temperature T_a	18.4°C
Air relative humidity RH_a	81%
Daily duration of sunshine S	7.1hrs
Latitude ϕ	1°
Wind speed, V_w	1.3m/s
Incident Shortwave Solar Energy	6.4 kWh
Rainfall	104 mm
Rain days	11.4 days

4.3 TEST RESULTS AND EVALUATION

In this section, results from the instruments functional tests to the final drying tests, are discussed.

4.3.1 Thermocouples and data logger functional testing

The results presented in Figure 4.8, are for the thermocouples inserted in the dish of sawdust. The highest temperature recorded was 24.6 °C and the lowest was 23.8 °C. The difference of 0.8 °C, was within the recommended range of 1.5 °C (PT, 2019).

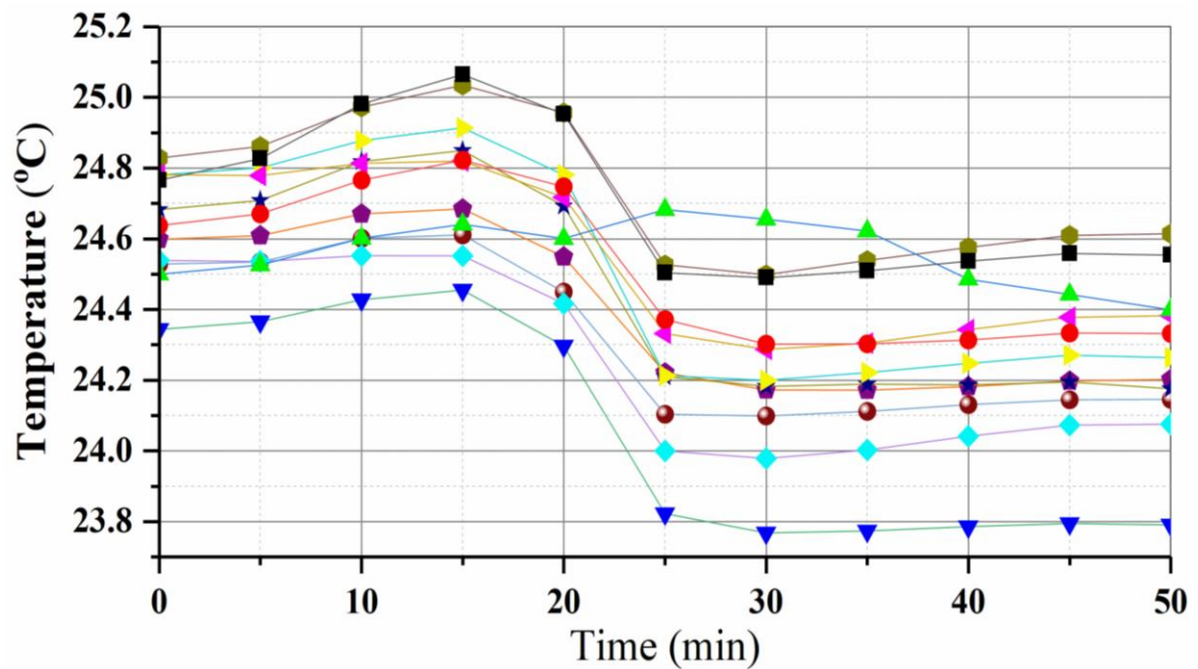


Figure 4.8: Data loggers and Thermocouples functional tests.

4.3.2 No Load Tests

4.3.2.2 Control tests-Solar only-with an electrical air heater control

Results of the temperature profiles of the solar collector, drying chamber and heat sink hole for a 35 hours, 45 minutes from (07:56)-17 April 2019 to 19:45-18 April 2019) trial period, are illustrated to enable ease viewing and analysis of the data, and due to similarities of the profiles. The data capture started on the second day after setting up. Figure 4.10 indicates the drying chamber humidity. Stacked graphs in Figure 4.11, show the temperature profiles for the, solar collector (SC), the HAC, drying chamber (DC), heat sink (HS), heat sinkhole ground (HSG), electrical air heater (EAH), ambient temperature (Amb.), and the drying chamber RH. The electrical air heater was set to cut-in at 37.5 °C and cutout at 48°C. Table 4.11 is a summary of the temperatures and RH achieved.

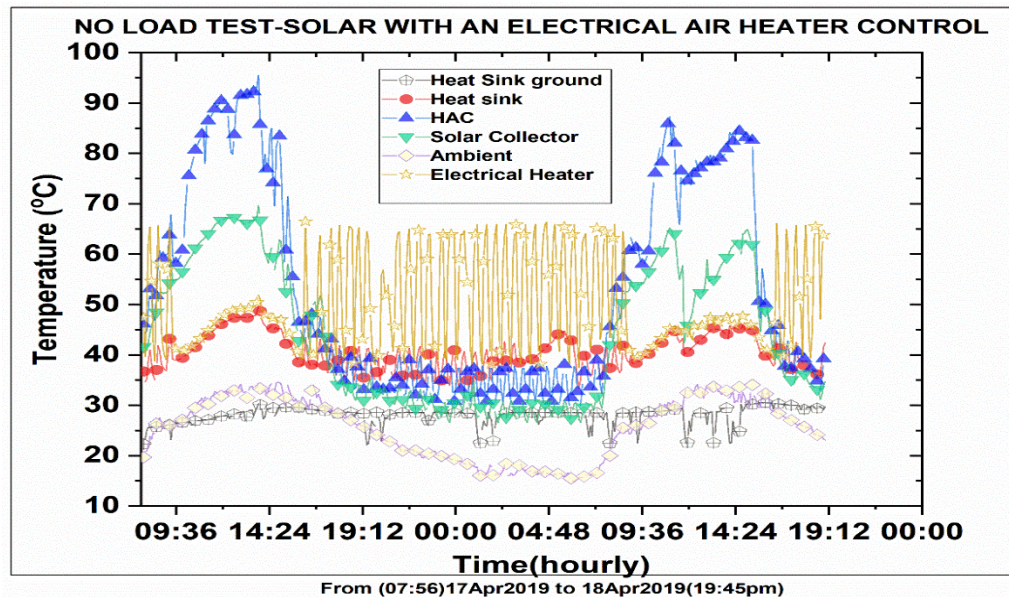


Figure 4.9: Control test results.

Point A

At 09:01(Point A) in Figure 4.11, the last circle of the 15-minute electrical heater cut-in, was observed, on April 17, 2019. At this point the Solar collector glass reported an average temperature of 52.6 °C, a temperature of 59.6 °C was recorded by the HAC, resulting in 43 °C in the DC, EAH was at 39.8°C, HS at 37.1°C, HSG temperature at 25.9°C and ambient temperature was 25.5°C. RH at this point was 37,8 %.

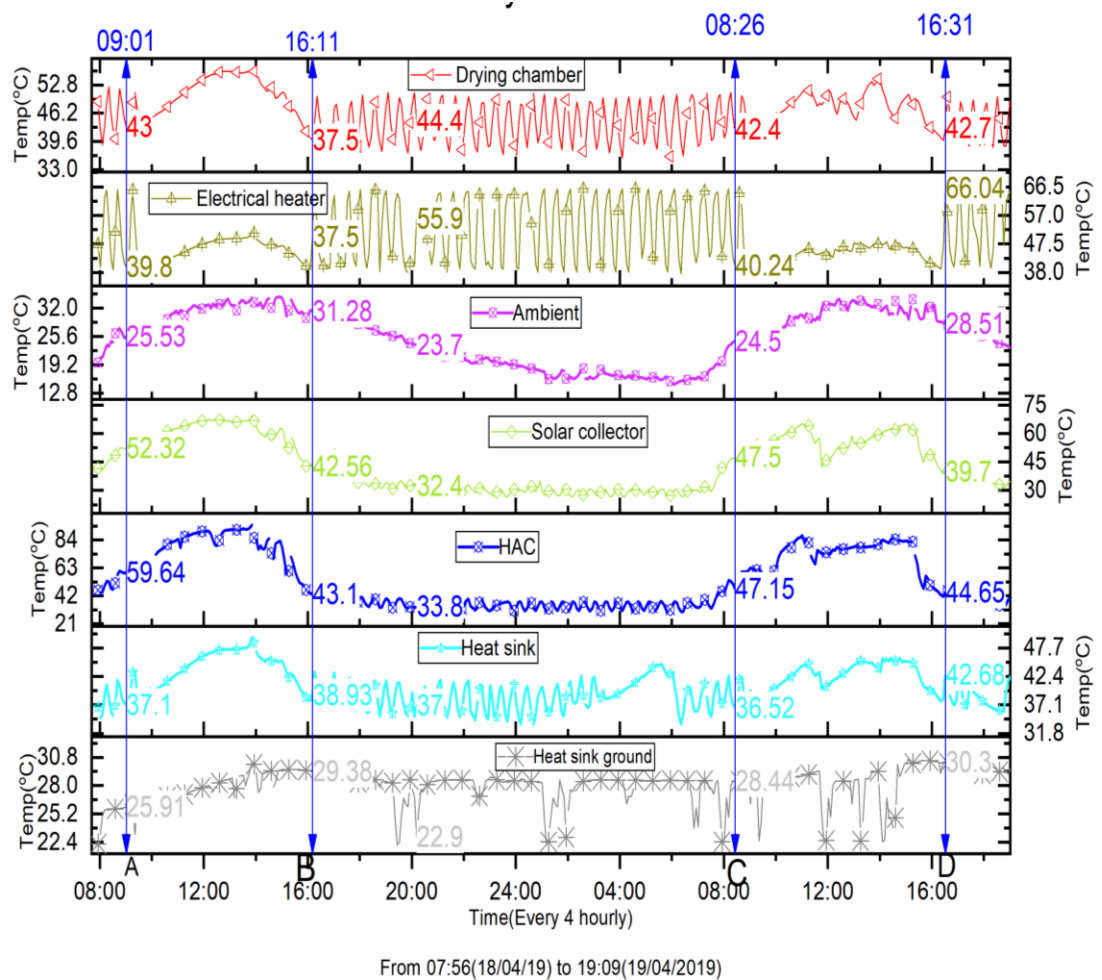


Figure 4.10: Stacked Temperature profiles for Figure 4.9.

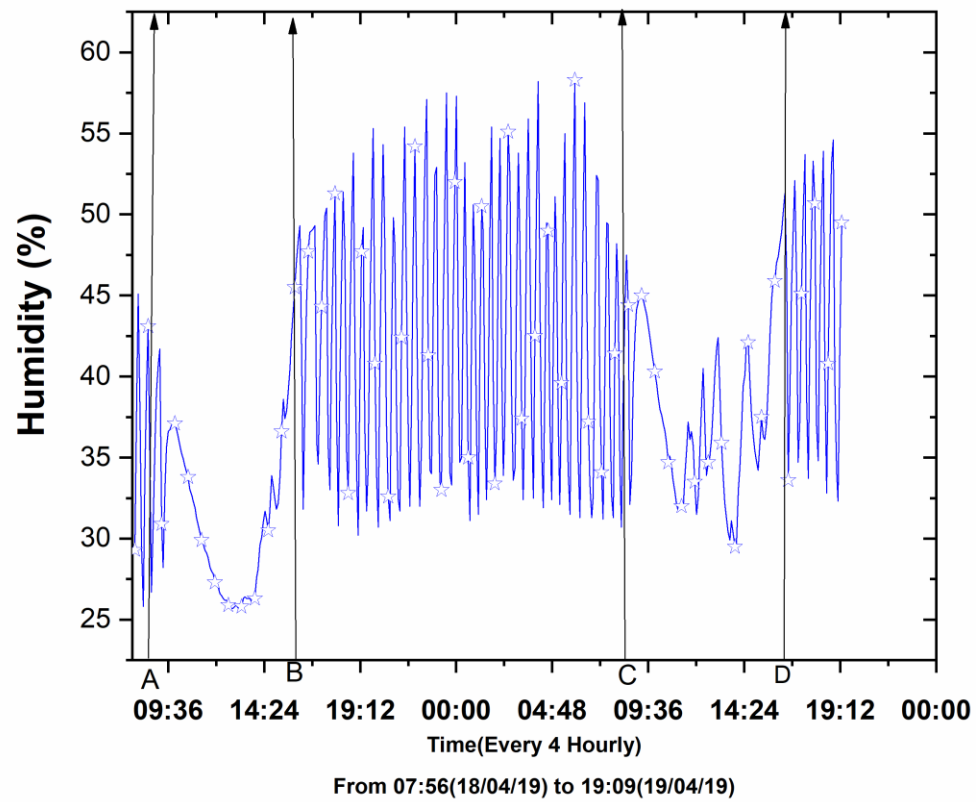


Figure 4.11: Drying chamber RH during solar-electrical air heater control tests

Table 4.11: Temperature/RH summary of the solar-electrical air heater control tests

Position	SC (°C)	HAC (°C)	DC (°C)	HS (°C)	HSG (°C)	EAH (°C)	Amb. (°C)	RH (%)
A	52.6	59.6	43	37.1	25.9	39.8	25.5	37.8
A-B	66.4	77.3	50.4	49.3	30.1	40.1	31.1	31.8
B-C	32.5	36.3	43.8	38.8	27.8	52.8	20.8	42.5
C-D	55.2	71.4	47.4	42.3	40.5	44.5	30.2	38.2
Average	51.7	61.2	46.2	41.9	31.1	44.3	26.9	37.6

Point A to point B (09:01 to 16:11) Refer to Figure 4.11.

The solar energy held the temperature above the cut-in temperature of the electrical air heater and at 12:45pm reached a peak of 56 °C, a minimum of 39.9 °C and an average of 50.4 °C in the DC. At 13:56, the solar collector glass reported a maximum temperature of 66.8 °C. Between this region, the average temperatures achieved were, SC-66.4 °C, HAC-77.3 °C, DC-50.4 °C, HS-49.3 °C, HSG-30.1 °C, EAH-40.1 °C, ambient temperature of 31.1 °C and RH of 31.8 %.

Point B to point C (18 April 2019 at 16:11 to 19 April 2019 at 08:26)-Figure 4.11

At point B at 16:11 on 17 April 2019, the temperature in the DC went down to 37.5°C from 50.4 °C due to the sun cover. The electrical air heater cut-in and remained on for 10 minutes before it went off at a temperature of 48°C. It took another 20 minutes for the temperature to drop to 37.5°C and the electrical Air heater to cut in again. The trend of the peaks and troughs continued up to 08:26 on 19 April 2019. The number of cut-ins and offs of the electrical air heater where analyzed and time calculated.

Point C to point D

On April 19, 2019, the solar cycle started again at 08:26 to 16:31. The HAC temperatures were; 71.4 °C average, 41.6 °C minimum and 87.33 °C maximum. The total hours the solar system provided temperatures above the lower set, temperature of the electrical air heater was 7 hours, 57 minutes. The temperatures of the solar collector were, 55.2 °C average, 65.2 °C maximum, and 39.0 °C minimum. The temperatures for DC were; 47.4 °C mean, 39.8 °C

minimum and 54.2 °C maximum. The mean of 38.2 % RH, achieved at minimum 29.5% and maximum of 50 % was achieved (Figure 4.10).

Drying Chamber achieved parameters (Mean)

The mean temperature and RH of 46.2 °C and 37.6 % respectively was achieved. The temperature was 19.3 °C above the ambient of 26.9 °C. The results are comparable to Aissa, et al (2014), where the dryer, reportedly attained 53.7°C but above what was achieved by Hegde et al (2015), 8 °C to 11°C above the ambient temperature (Aissa,El-Sallak, & Elhakem, 2014; Hegde et al., 2015).

Energy Values

The energy used by the electrical heater, was the average energy consumptions recorded from the Energy data logger. Total time the Electrical air heater was on was 7hrs 45 minutes and the average rated energy consumed was 750w resulting in the consumption of 5.8 kWh. On average, the electrical air heater was off for 8hours 25 minutes. The rapid cut-ins and offs of the electric air heater can be due to the weak thermal insulation of the drying chamber system. The energy produced during the solar hours was 42.02kJ. This experiment showed that during good solar hours, drying is possible with less energy consumption (Khoukhi & Maruyama, 2006).

Discussion of the results control test (solar and electrical air heater)

The experiment average HAC temperature attained was 61.2 °C, higher than the average SC temperature of 51.7 °C. This is so because, glass is considered as cover for solar thermal equipment due to its absorbability property. It absorbs almost all the infrared radiation that bounces back from the black painted surface of the HAC resulting in the good thermal

efficiency of the solar collector due to the greenhouse effect created (Khoukhi & Maruyama, 2006).

The average RH in region A-B and C-D were 31.8 and 38.2 % respectively. The downward troughs on Figure 4.10 show this. During the nighttime the RH was varying in corresponding to the on and offs of the electrical heater. This effects shows that the higher the drying air temperature is in the DC, the more significant the effect id on the drying chamber kinetics. This enables fast evaporation of moisture hence quick drying. This principle was explained by other researcher who deduced that higher air temperature had more effect on the drying rates than increase air velocity drying Kenaf (Misha, Sohif, Ruslan, & Soplan, 2013).

4.3.2.3 No load Solar only test during the rainy season

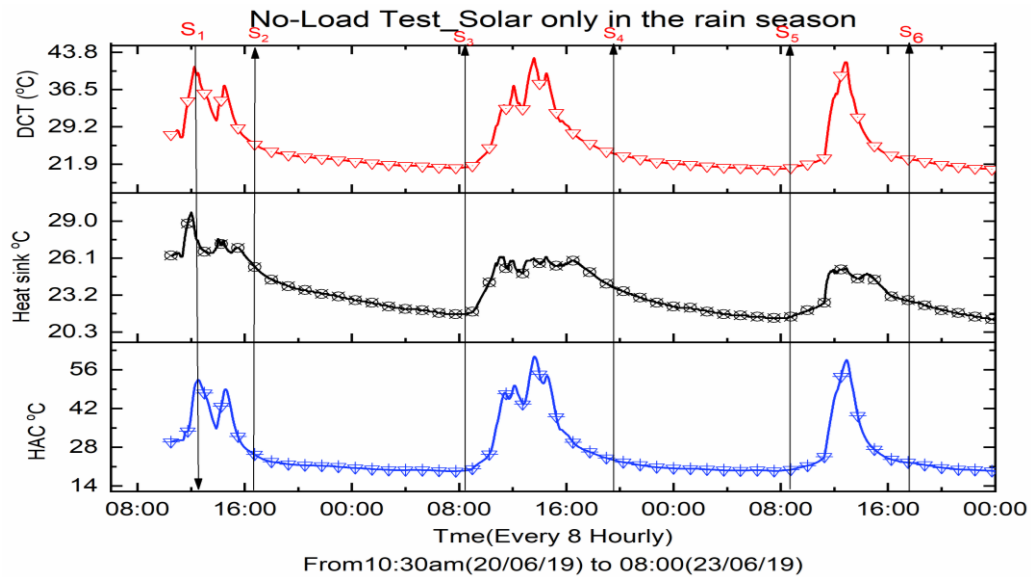


Figure 4.12: No-Load test solar only in the rain season

Figure 4.12 and Figure 4.13 shows the drying system temperatures and R.H/temperature profiles for the DC respectively, during the solar only heat source trial. Results in this section are based, on Figure 4.12 on temperatures. The tests started at 10:30 am with, 20.6 °C, HAC bottom plate temperature, 25.1 °C in the pit bottom, 24 °C in the DC on 20 June 2019. The relative humidity at that initial point was 51.1%. For easy viewing and analysis, shown results are for the period of 3 days only.

Period S₁ to S₂

At 12:15 on 20 June, the peak temperature of 41 °C was realized in the DC at R.H. of 51.1%. Between S₁ to S₂ (10:30 am to 17:13) on 20 June, the solar energy contribution was high and resulted into the average R.H. of 69.6 %. The pit bottom had an average temperature of 26.8°C.

Period S₂ to S₃

The region between S₂ and S₃ shows the off solar hours from 17:13 on 20 June 2019 to 09:00am to 21 June 2019 when the temperature in the DC decreased from 25°C to 21.6 °C. The average ambient temperature in this region was 16.1°C at an average R.H. of 98.2%.

S₃ to S₄ (09:00am to 19:12 on 21st June, 2019)

The average DC temperature between the periods attained 30.5 °C with a peak at 13:38 of 42.7 °C. The average R.H. in this region was 67.4 % at an ambient of 23.3 °C. The solar irradiance provided more energy to the absorption chamber hence the rise in the temperatures

and the RH drop. The cycle repeated from region S_4 to S_5 (During the night) as in S_2 to S_3 . The average R.H. and temperature in the DC was 96% and 21.9°C respectively (Figure 4.13). Cycle S_5 to S_6 is also similar to cycle S_3 to S_4 .

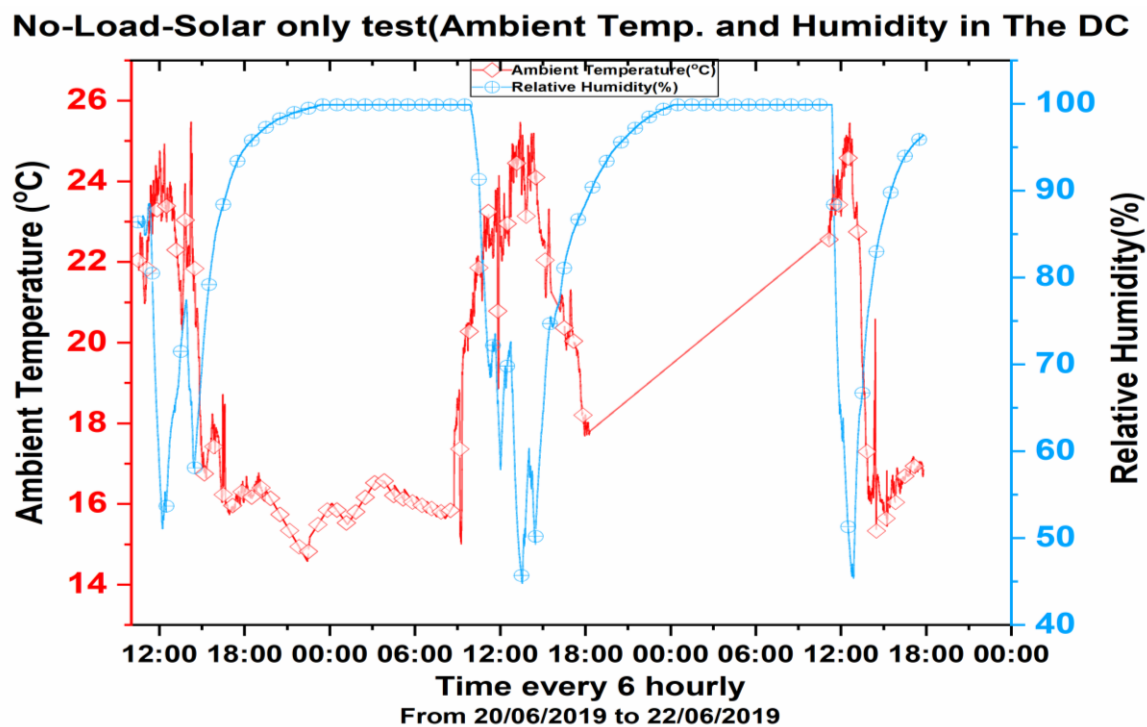


Figure 4.13: No load -solar only tests results (Ambient and R.H.).

On average the DC during the no load solar only trial tests shows, the mean R.H. of 89.6 %, minimum R.H. of 44.8 % and maximum of 99.9 %. The average temperature was 25.5°C. The results show that nighttime drying is not feasible. Kalogirou (2014) recommends a drying temperature of at least 30 °C and an average drying chamber temperature of 60 °C. Consequently, the findings during the solar tests also reveal that the dryer cannot be used with solar only to dry efficiently for longer hours (Kalogirou, 2018).

4.3.2.4 Heat absorption chamber Water heated with electrical heater.

Figure 4.14, shows the temperature profiles for the HAC, DC, Heat sink and ambient from 31 May 2019 at 08:45 to 4 June 2019 at 19:12, when the water in the HAC was heated by an electrical water heater rated 300W/700W (Figure 3.8, Section 3.4.4). The heater consumed 400W on average. The initial temperatures were, HAC 33°C, DC-25°C, Bottom heat sink hole 25.4°C and an ambient Temperature of 18.4°C. The water in the HAC was 240kg. The water temperature sharply increased as follows; HAC, from 33°C to 53.9°C, DC, from 25°C to 34.9°C, bottom heat sink, 25.4°C to 29.4°C at an ambient temperature of 18.6°C at point A within 10 hours.

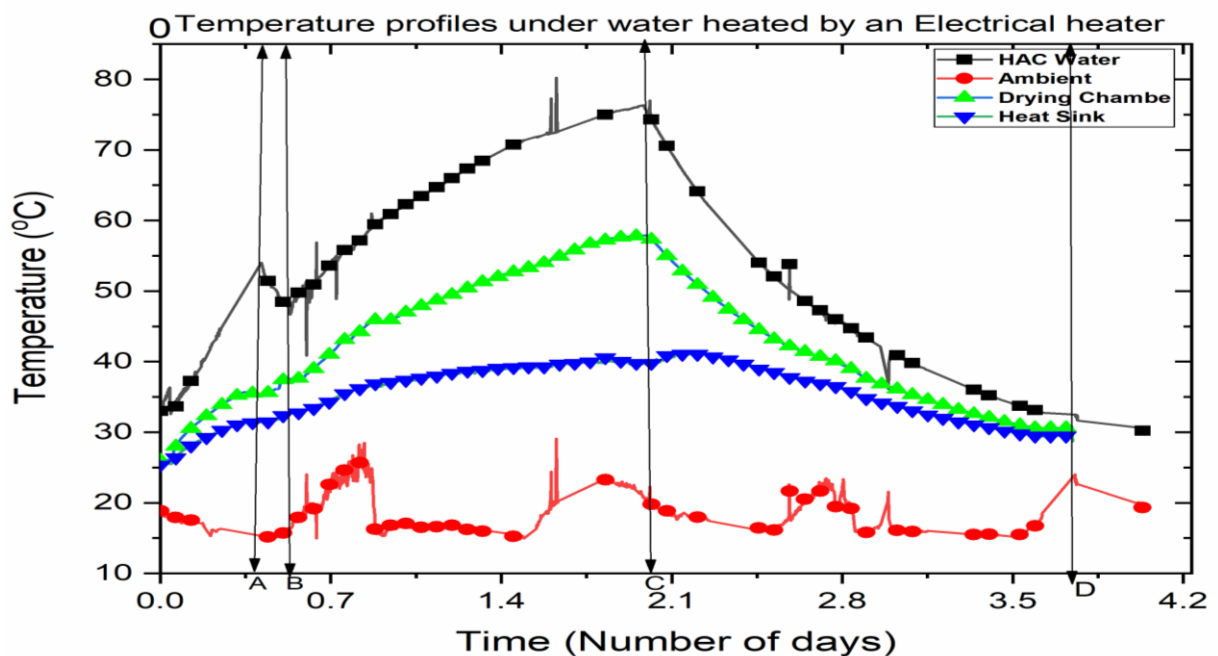


Figure 4.14: DC conditions under the Water electrically heated tests.

Between point A-B in Figure 4.14, power outage was experienced for 2.5 hours and the temperatures dropped to, HAC-48.25 °C at a rate of 2.3 °C/hour, before power was restored. From Point B to C, the temperature increased to 76.1 °C in the HAC, 57.9 °C in the DC, 39.9 °C in Bottom heat sink hole at an average ambient temperature of 18.8 °C. The electrical water heater was switched off at 18:00 on 2 June 2019, when the HAC temperature was 76.1 °C, DC at 57.9 °C, taking 47.5 hours. Natural cooling down of the water took place from 2 June 2019 at 18:00 to 19:12 on 4 June 2019. The water-cooled to 32.5 °C in the HAC and 39.5 °C in the DC. The DC bottom pit helped to conserve some heat, hence the slower rate of cooling as compared to the HAC. The rate of cooling was 1.04 °C/hr in DC and 0.84 °C/hr in the heat sink hole.

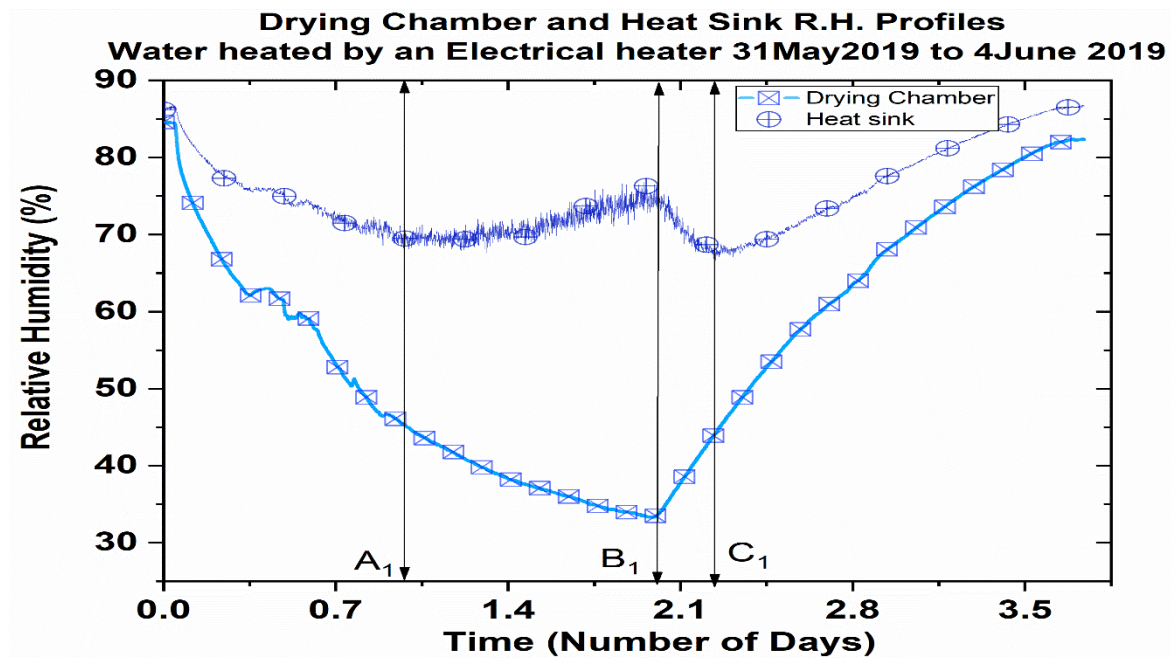


Figure 4.15: Comparison of the R.H. in the DC and Heat sink under water heated electrically tests

The RH increased from 33.4% to 82.4 % during the cooling period in the DC and from 68.3% to 86.7% in the heat sink as shown in Figure 4.15. From point A1 to B1, Heat sink hole moisture absorption capability was demonstrated. As the R.H. in the DC, decreased from 45.1 % to 33.4 %, the heat sink hole RH rose from 70.1 % in 24 hours to 77 %. The RH increase in the HS because part of the air cooled down, became moist and heavier. The moist air sinks to the HS and part of the moisture is absorbed by the ground which acts like a subsurface geothermal resource and is widely used for heating and or cooling in buildings. This principle enhances energy recovery and efficiency (Brandl, 2013).

During the cooling of water, the DC's R-value was 0.99 as opposed to the R-value of the heat sink hole of 0.94. That indicates that the DC was losing heat at a much faster rate than the heat sink hence realizing more moisture to the heat sink. The slopes were 0.02 and 0.0082, DC, heat sink hole, respectively.

Energy Values

The total energy consumed by the electrical water heater to heat the water (HAC) from 33°C to 76.1°C, was 18.2 kWh resulting into 0.4 kW/h (45hours). Total energy required to heat water from 33°C to 76.1 is 12.1 kWh resulting into 0.3 kW/hour (45 hours). Energy generated in the DC by heating air from 25°C to 57.9°C was 0.02 kWh resulting into 0.0005 kW/hour.

Due to conductivity and convectional losses, the heater utilized more energy. The drying chamber achieved the mean temperatures of 42.7°C to 57.9 °C at an average RH 56% .The heat sink bottom absorbed 75 % RH on average as shown in Figure 4.15. At the highest

temperature of 76.1 °C, RH of 33.3 % and 66.6 % in the DC and Heat sink hole attained, respectively.

The achieved temperatures and R.H were in conformity to the low temperature drying conditions recommended by previous researchers (Mutali & Mbugu, 2015) who established that drying Cowpea at 40 °C, consumed less energy 11.2 j/g than drying the same at 100 °C (168J / g) (Chauhan & Rathod, 2018).

4.3.3 COMPOST REACTOR AND COMPOST HEAT EXCHANGER THERMAL PERFORMANCE

4.3.3.1 Temperature and Energy Values

Temperatures

Figure 4.16 shows the average temperature profiles between 4 June 2019 and 19 June 2019 (day 1 to 19th day). The compost reactor temperatures reached above 60 °C after 1.88 days and highest values of 68.9 °C, were recorded, on 6 June 2019 at 13:57 from a starting point of 25.5 °C before decreasing to a mean of 41.1°C on 28 June 2019. The time is in agreement (2-4 days) with that observed when composting with one direction of airflow Ekinci (2001) but higher than the observed by Keener et al (1991) of 8 days using high recirculation of air that was processed and took 0.63days (Ekinci, 2001; Keener et al., 1991). A compost reactor achieved temperatures of 60°C after two days from an in-vessel tunnel composting facility in Scotland and 65°C while compost Horse based manure, after four days by Irvine et al (2014).

A temperature of 60°C was achieved, during winter using a 1.5 to 2 meters compost depth (Finstein et al., 1986) using a passively aerated static reactor with enhanced aeration by means of channels arranged vertically. Bajko et al (2018), achieved similar temperature rise of 65°C in 2 days.

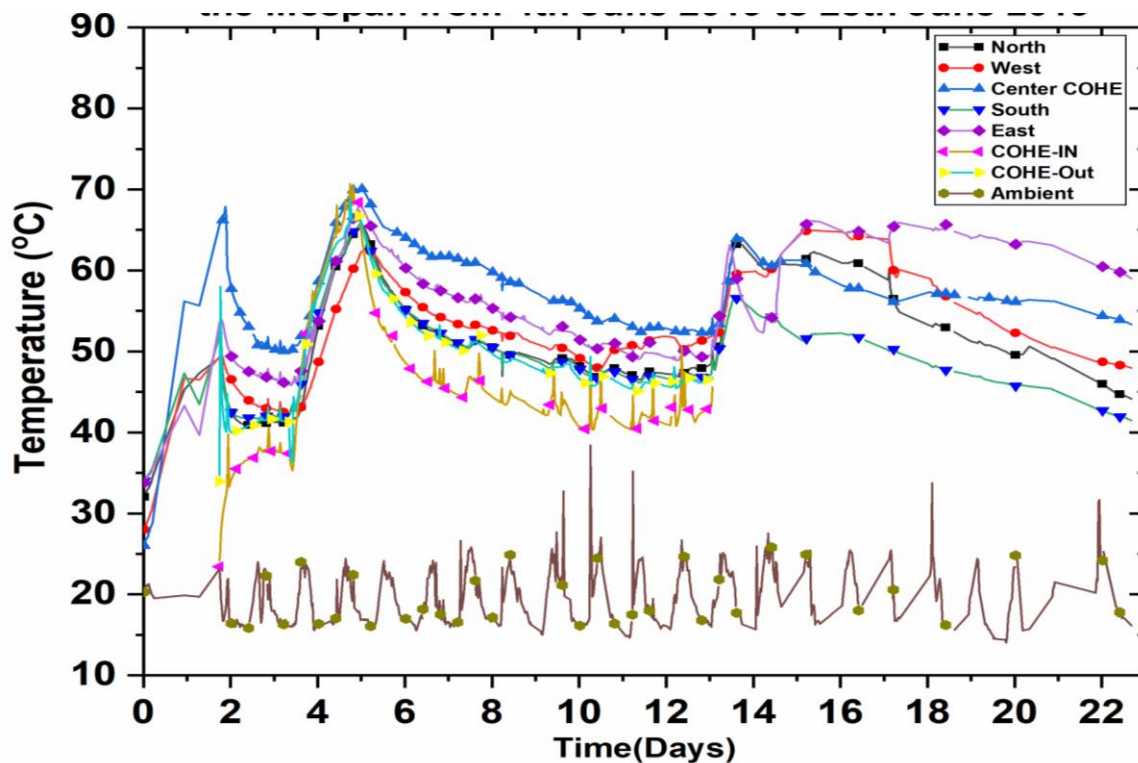


Figure 4.16: Compost reactor and COHE (in/out) average temperatures (22 days span).

4.3.3.2 COHE thermal flow performance

The results of the COHE_{IN} and COHE_{OUT} pipe outlets for a trial period of 13 days from 6 June 2019 to 19 June 2019 are shown in Figure 4.17, indicating the useful energy in terms of water-heated temperatures and energy generated by the COHE. A series of peaks and troughs

where observed during the times the COHE was operational. The COHE, was operationalized when the compost reactor average temperatures were above 65°C on 6 June 2019 at 13:35 (day 1.74). The initial temperature of water in the HAC (COHE_{IN}) was 23.4°C as shown in Figure 4.16 at A₁. Upon turning on the recirculation pump, the COHE_{OUT} temperature was 33.9°C, at an ambient of 21.5°C and Compost Reactor temperature of 65.6°C. At this time set (1.74days), COHE_{OUT} and COHE_{IN} difference was 10.6°C as shown in Figure 4.18 at A₃. Within 30 minutes, the COHE_{OUT} temperature drastically increased to 58.1°C as denoted by B₁. The HAC temperature consequently rose from 21.5°C to 25.5°C.

However, the COHE_{OUT} temperature sharply decreased from 58.1°C to 40.4°C within 5 hours at (1.96days) denoted by B₂ (Figure 4.10) and the HAC (COHE_{IN}) temperature had increased to 33.7°C, the compost reactor temperature went down to 61.9°C. The sudden drop was due to the dilution of the COHE water temperature with the HAC cold water. Between B₂ to C₁ (16:27 to 19:45pm) on 7 June 2019, the temperature remained constant between 40.1 °C to 42 °C in the COHE_{OUT} and 30 °C to 38 °C in the COHE_{IN} the average ΔT been about 10°C. On 7 June 2019 at 17:53, denoted by C₁ to C₂, the Pumping system was stopped briefly to seal the water leakages hence the trough shown C₁ to C₂. The temperatures from the COHE went down from around 41°C to 36.2 by 07:28am on 8 June 2019. At these time set the COHE_{IN} temperature was at 34.9°C, ambient was 16°C and around average of 51 °C from the compost reactor. The quick rise and drop of the temperature was also experienced by (Allen & Chambers, 2009), where an initial activation of the heat extraction using a compost heat extractor with the fluid mixed with water and Glycol was used to heat the water from 5°C to 48°C, but dropped to 38°C after 5 minutes. Bajko et al (2018) reported the strategy of finding

an amount of heat that could be extracted without affecting the composting process dynamics. This was done by, staggering the extraction rates and times. At point X_1 , X_2 , X_3 and 1, 2 and 3 (Figure 4.17), average temperature peaks of up to 8°C , were witnessed because of the daytime natural solar radiation heating the water in the HAC via the solar Collector, high ambient temperature passing through the compost reactor through the chimney effect. The peak decreases as soon as the solar radiation decreases. Figure 4.18 highlights the solar radiation induced peaks at C_3 .

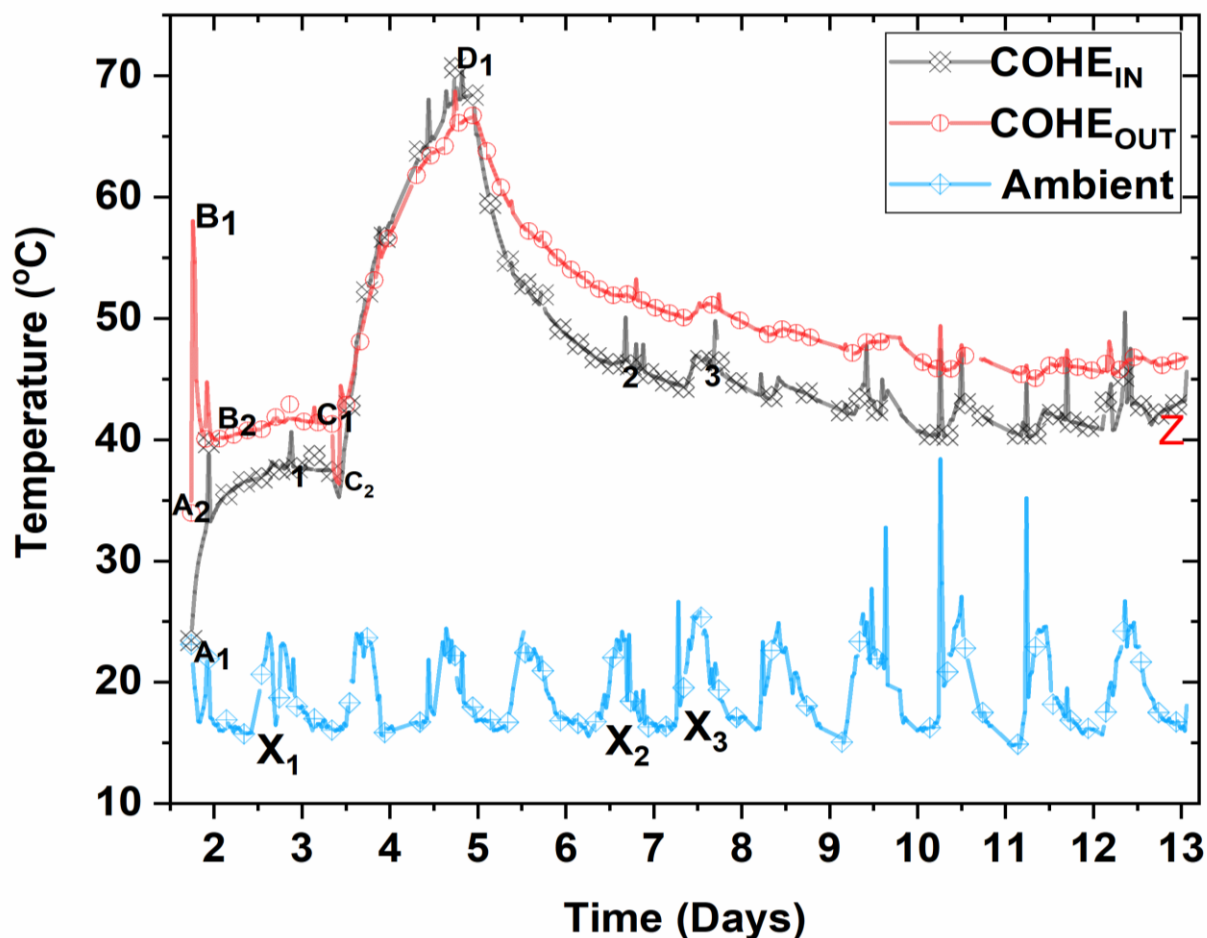


Figure 4.17: COHE (IN & OUT) temperature profiles (6/06/19 to 19/06/19).

On 8 June 2019 at 07:29, the compost reactor average temperatures dropped to around 51°C and it was decided that the HAC water be heated using a 400/750w water heater procured locally. The decision was in order to keep the system temperatures above 55°C and activity C₂ to D₁ in Figure 4.17 depicted. The water in the HAC attained 70.1 °C and the heater was turned off at 20:58 on 9 June 2019 after operating for 37 hrs and 29 minutes. The total electrical energy used by the heater 28.1kWh. This resulted in the negative COHE_{OUT} - COHE_{IN} depicted on Figure 4.18 at D₃ to E₃. The compost average temperature rose to 69 °C. The pattern of having the positive value for temperature difference resumed after the electrical water heater, was switched off. The average difference temperature throughout the heat extraction period from 6 June 2019 to 19 June 2019 was 3.5 °C. The maximum COHE_{IN} temperature was 70.1°C and 68.7 °C for the COHE_{OUT}, minimum of 23.4 and 33.9 °C respectively. Ambient Temperature was 14.6 and 38.4 minimum and maximum respectively. Figure 4.18, is a summary of the average temperature profiles (ΔT) between COHE_{OUT} and the COHE_{IN}. Extracted Energy from the COHE values were then calculated using temperature differences.

4.3.3.3 Energy generated, extracted and COP of the COHE.

The extraction of heat started on day 1.74 at the initial COHE_{IN} water temperature in the HAC of 23.12 °C. The COHE_{OUT} temperature sharply increased to 58.02 °C within 28.8 minutes. The sharp rise of temperature can be attributed to the reserve water within the COHE piping system calculated to be 0.036 m³ (36 litres or 36 kg of water) of water. The volumetric flow of the pump was, 0.000025 m³/s translating into 0.025 Litres/s equivalent to 0.025 kg/s. To pump out the reserve water from the COHE pipes, 1360 seconds (22.7 minutes) were

required. Due to the extraction of heat energy on this day for the first time, the compost energy began to decline. The energy in the compost reactor decreased to a low of 460 MJ on day 24 of composting.

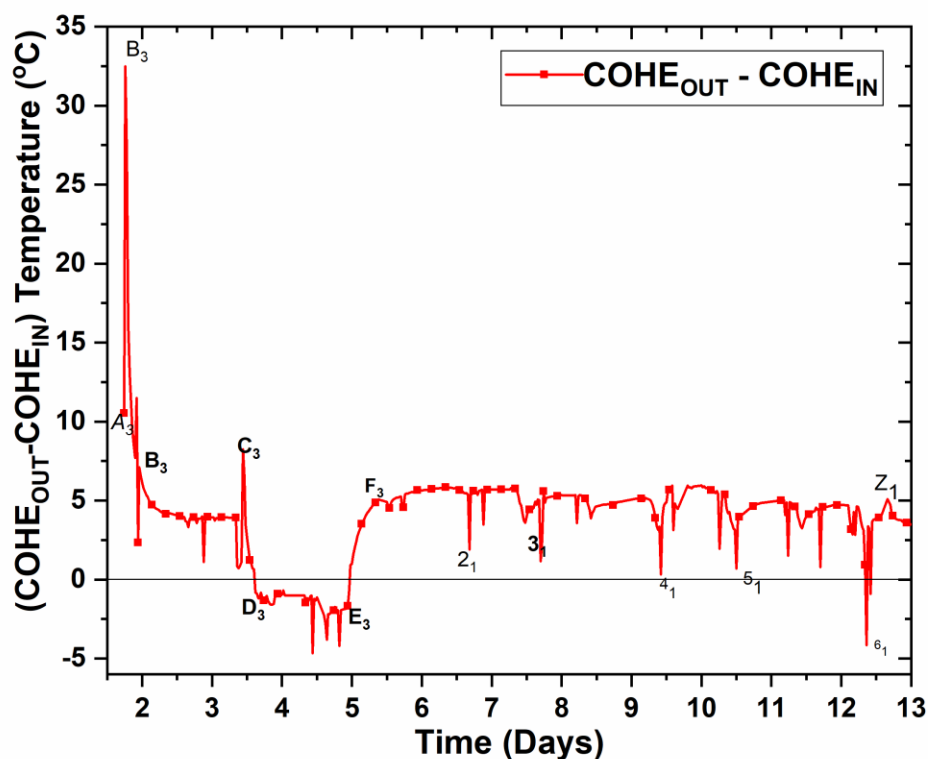


Figure 4.18: Temperature differences between the COHE out and COHEin during extraction

Figure 4.18 shows the temperature differences between the COHE_{out} and the COHE_{in}. It shows that the highest temperature difference was attained at B₃ (32.51 °C) immediately after commissioning the extraction. The system had a negative difference between C₃ to D₃ (8.26 °C to -1.32 °C) and D₃ to E₃ (-1.25 °C) average. This was the period when the electrical water

heater was used and increased the temperature of the HAC water hence giving rise to the negative ΔT . Between E₃ and F₃, the electrical water heater was not operational and the net ΔT moved from negative to positive 4.95 °C at F₃. The solar radiation increased the temperature as indicated on point 2₁, 3₁, 4₁, 5₁, and 6₁. This shows the solar contribution to the hybrid system.

The energy extracted by the COHE values were calculated using the average temperature differences described in Figure 4.18 and summarized in Figures 4.19. The energy within the Compost reactor, with the cumulative heat energy extracted, at each time interval, worked out and presented in Figure 4.20 together. The energy stored in the compost reactor increased from 106 MJ to a peak of 286MJ on day5 (9 June 2019). The results are in the same range as Allen & Chambers (2009) who achieved 279 MJ to 326 MJ on day number 4. During the trial period, the compost energy decreased to 210MJ (Allen & Chambers, 2009).

Cumulative extracted energy increased to 727 MJ, from 6 June to 19 June 2019 during the extraction trials. The total energy extracted in kWh was 202 kWh. Now the energy used to heat the water from the electrical heater was 28.1Kwh. Therefore the net average energy extracted was 174Kwh, translating into 7.8 kg/kWh or 538kJ/kg per initial mass compost weight matter and 1273kJ/kg on dry matter. This energy values are in the range generated by Allen & Chambers (2009) of 5.7 kg/kWh, but less than those reported by Irvine et al (2014) of 6000 kJ/kg/day and Finstein et al (1986) of 2791 kJ/kg/day from straw and poultry manure. However Keener et al (1991) reported 2435 KJ/kg/day when composting paper mill sludge with the boiler litter (Keener et al., 1991).

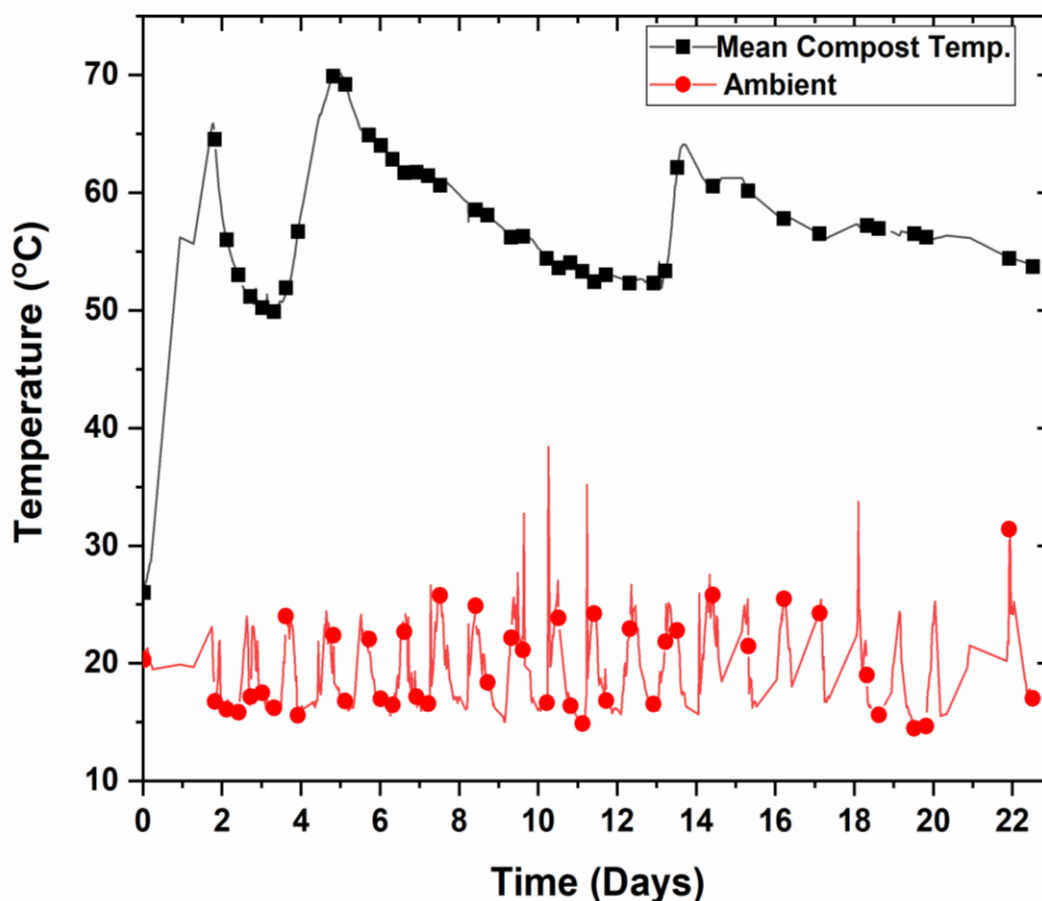


Figure 4.19: Mean compost reactor and ambient Temperature.

The 1273 kJ/kg DM recovered is in the range reported by Smith et al (2017) of 1159 kJ/kg for pilot scale and 4302 kJ/kg DM. For commercial 7084 kJ/kg was reported (M. M. Smith et al., 2017). A 510 kJ/kg DM heat recovering has been reported recently (Bajko et al., 2019). Discrepancies in cumulative energy values are due to differences in the methods and rates of decomposing subjected to different conditions such as thermal insulation, feedstock types, and methods of extraction. This makes direct comparisons difficult to arrive upon and ultimately ineffectual. However, the values achieved in this research are comparable to other researchers and are reliable.

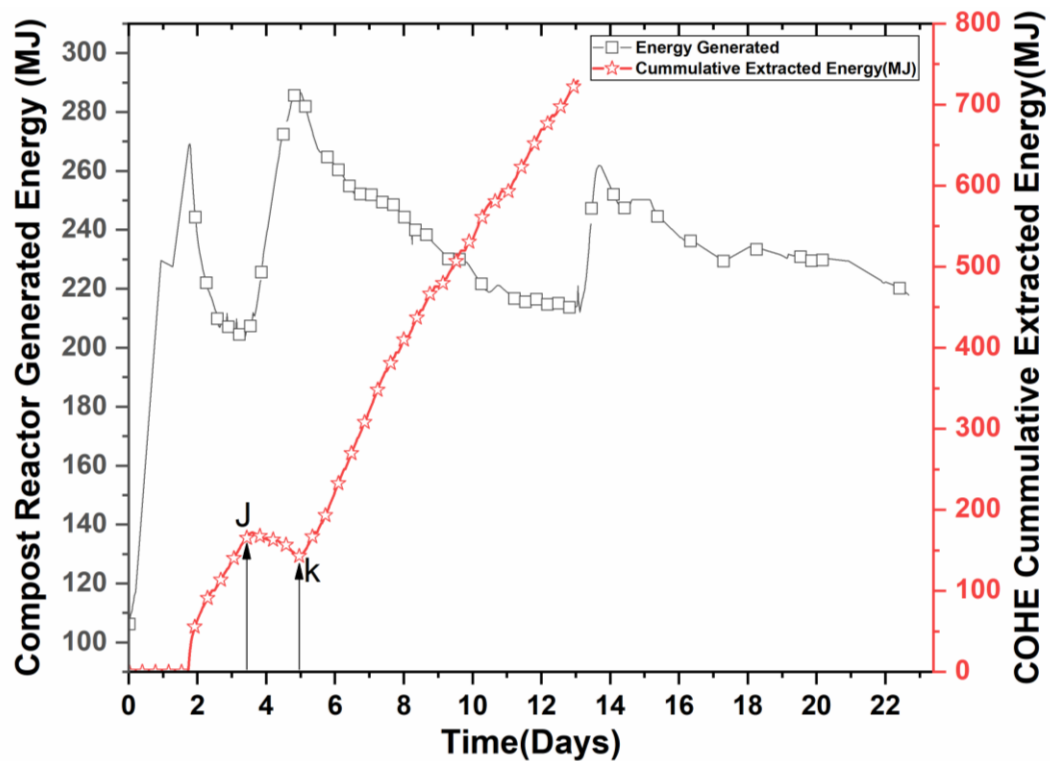


Figure 4.20: Compost reactor generated energy (4/06/19 to 28/06/19) and COHE cumulative extracted energy (6/6/19 to 19/6/19).

From point J to point k in Figure 4.20, the extracted and generated energy dropped from 173 to 144 MJ and 268 to 205 MJ respectively as depicted on J to k.

4.3.3.4 Coefficient of Performance of the COHE

The COP was calculated using Equation 2.8

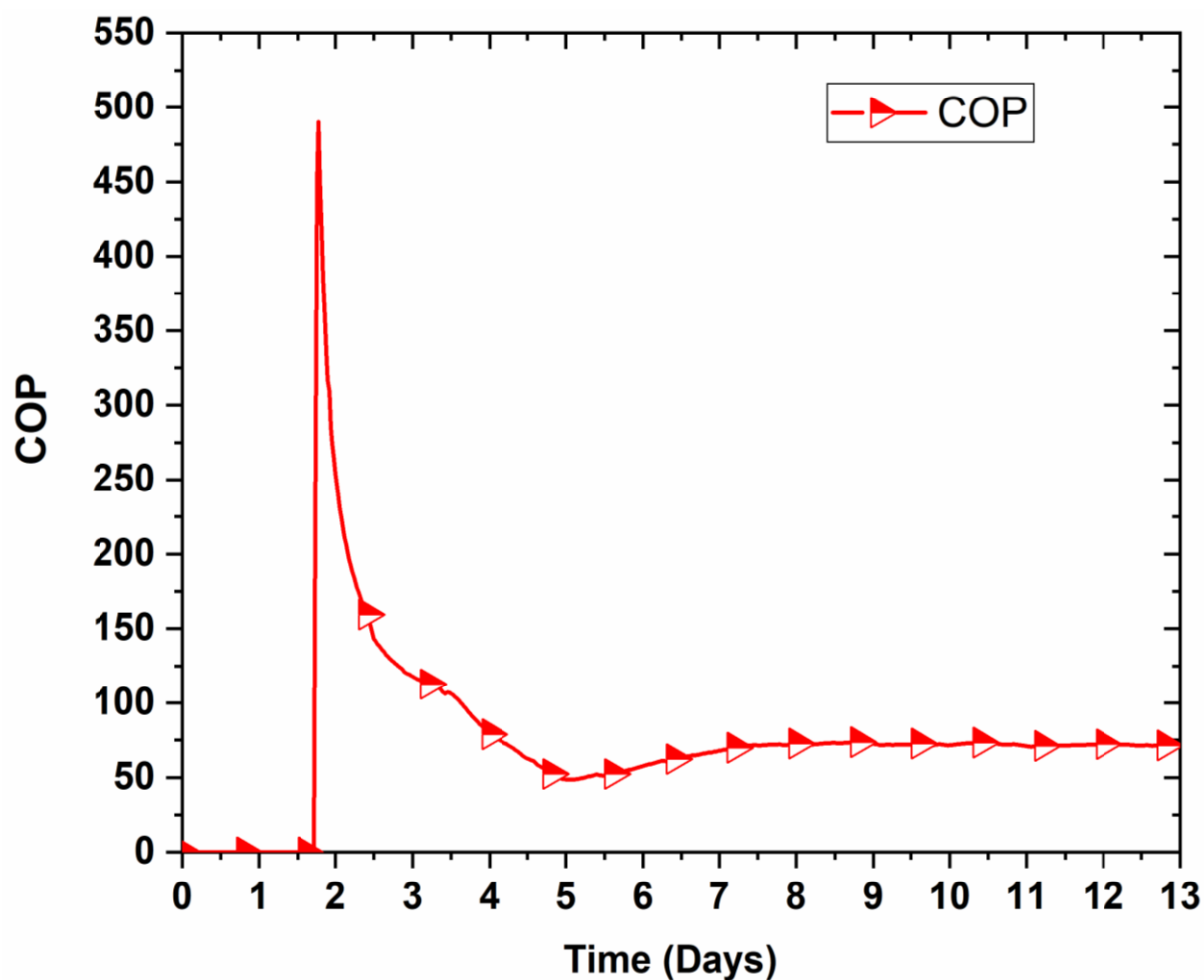


Figure 4.21: COP of the COHE during extraction (6/6/19 to 19/6/19)

In Figure 4.21, the Coefficient of Performance (COP) attained by the COHE during the extraction period, is indicated. During the first 1.74 days, the COHE was not activated hence zero COP. Throughout the trial phase a high COP was achieved and peak was recorded after 96 minutes of activating the COHE pumps at 489.9. The average energy used by the pump

throughout the trial period was 2.7 kWh at an average of COP 74.22, maximum of 489.9. The COP gradually reduced to 71.5 on day 13. The results are higher than (Allen & Chambers, 2009), where a maximum of 12.5 COP was achieved while extracting heat from the compost reactor using a Grundfos UPS 15-50 130' flow pump rated at 55.2w, 230 ACV, 3.4m³/hr and 6m maximum head as compared to the pump used in this project of 5w and 48 DCV power requirement. The different power consumption explains the difference in the COP. The less energy the pumping system uses per energy generated, the higher the COP.

4.3.4 Summary of drying chamber condition during different sources of heating

Table 4.12: Drying Chamber conditions under different heat sources

Source	Mean Temp. (°C)	Mean R.H. (%)	Mean Ambient Temp.(°C)	Max. Temp. (°C)	Energy Generated (kWh)	Energy Used (kWh)	Net Energy (kWh)
1. Control	46.1	39.2	25.5	56	9.1	20.16	-11.1
2. ¹ SORS	24.5	89.7	18.7	42.7	2.6	0.96	1.6
3. *EHW	42.4	55.8	18.3	57.9	10.7	20.16	-9.5
4. Compost	41.5	43.6	18.0	56.1	10.4	1.2	9.2
5. Hybrid (Solar & Compost)	50.2	42.2	18.1	60.1	15.8	1.2	14.6

*Electrically heated water, ¹Solar only in the rainy season.

Table 4.11 points out the conditions of the DC under various heating sources and routes. The energy, relative humidity and temperature profiles (mean, maximum and minimum) in the drying chamber, during the control test (solar and electrical air heater), solar only during the rainy season test, the HAC water heated by the water heater test, and the water heated by the compost reactor in the COHE, are analyzed.

The control test using a hybrid of solar and electrical air heater consumed 20.2 kWh and generated 9.1 kWh in the DC. The net energy was negative 11.1 kWh meaning that the system consumed more to generate the required DC drying conditions. During the rainy season, the solar only heated, achieved an average RH of 89 percent and average temperature of 24.5 °C resulting in net energy of 1.6 kw after using 0.96 running the air recirculation fans. This condition does not meet the requirements for drying at low.

The HAC's electrically heated water attained 42.4 °C and 55.8 % mean temperature and RH respectively, consuming 20.16 Kwh, resulting in a negative net energy of 9.5 kWh. The negative indicates that it consumed energy from the national grid for heating the water. The Control, EHW and Compost heated drying chamber periods, resulted into the conditions that are required for low temperature drying. In the drying chamber, the compost heated system reached a mean of 41.5 °C and 43.6 percent temperature and R.H. The system consumed 1.2 kWh and generated 10.2 kWh, resulting into a 9.2 kWh net energy. That means that the system generated more energy than consumed. This result shows that composting heat extraction can be cost effective and compare positively with the electrically heated systems. The solar thermophilic Hybrid, setup generated 14.6 kWh net, at maximum DC temperatures of 60.1 °C and mean 50.2 °C, with R.H of 42.2 %.

Therefore, the compost-heated system attained the conditions recommended for low temperature drying. (Sagar & Kumar, 2010). The load test drying of the cowpea leaves proceeded, after meeting the minimum conditions required for drying at low temperature.

4.4 COMPOST HEATING DISTRIBUTION AND DRYING PERFORMANCE ANALYSIS

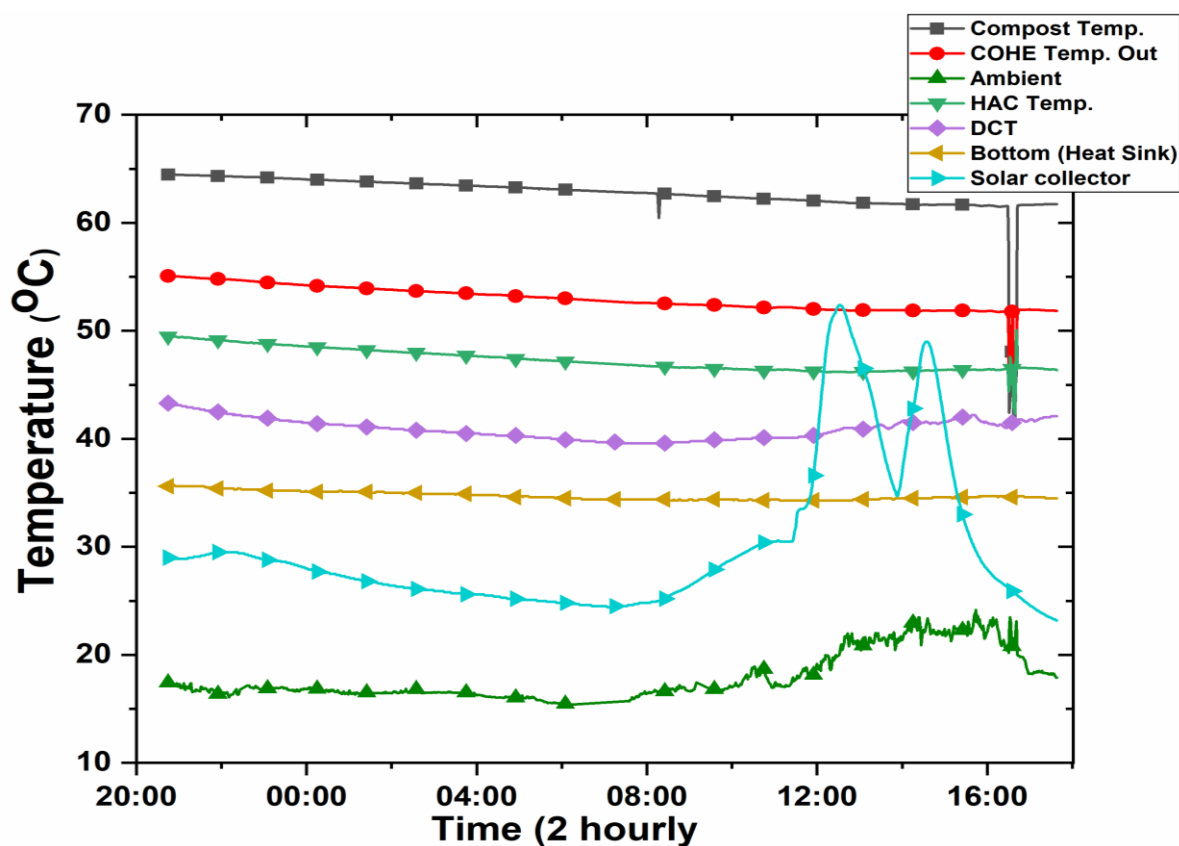


Figure 4.22: Temperature matrix for compost heated system during drying tests

4.4.1 Heat distribution analysis

Figure 4.22, shows the temperature profiles of the thermophilic dryer system heated by the compost reactor and solar collector during the drying tests. Results for a short period of 18 hours, are shown, to allow ease viewing and data analysis. In addition, this technology had its best energy output during this time hence focusing the results here. The maximum compost reactor and ambient temperatures were 64.5 and 24.5 °C & average of 62.7 and 18

°C respectively resulting into an average temperature rise was 44.7 °C above the ambient. The solar collector had a maximum temperature and average temperatures of 52.4 and 29.1 °C respectively resulting into a difference of 11.1 °C above the ambient. The temperatures resulted into raising the COHE water temperature to an average of 52.9 °C (55.1 °C max.) and 34.9 °C above the ambient. Consequently, the DC temperatures on average were 40.9°C at an average of 40 % RH and maximum of 52.5 °C. The exerted air from the drying area to the heat sink pit bottom was on average of 26.7 °C at average 88.7 % RH. The water pumped from the HAC to the COHE, was at an average of 47.3 °C. The attained conditions indicate that the drying system made was capable of being deployed for vegetable drying that require drying chamber temperatures of 40 – 60 °C (Mbaka & Mwaniki, 2016).

The slope for the compost reactor temperature was -4.7 ± 0.2 ; the COHE was -4.2 ± 0.1 , the HAC water temperature -3.8 ± 0.1 , the DCT -0.8 ± 0.1 and the heat sink hole 0.1 ± 0.1 . This indicates that the main source of heat was the Compost reactor through the COHE that heated up the water in the HAC. Through the HAC bottom plate and the fan action on the air, the heat was circulated throughout the drying chamber compartment. The negative slope indicates that the system was giving away the heat energy. The heat sink hole had a positive slope indicating that it was receiving the heat from the diffused air from drying chamber (Moist air). The moisture in the air was been absorbed by the soil resulting in less heavy air rising again into the DC. This saves the energy that otherwise could have been given away to the outside environment to be reused in the drying system.

4.4.2 Drying performance analysis

The drying Chamber had the average and maximum temperatures of 47.9 and 52.3 °C respectively and mean of 32.9 and maximum R.H of 49.2 %, before the tray doors were opened (before drying commenced).

4.4.2.1 DC Temperature and RH analysis during drying trial

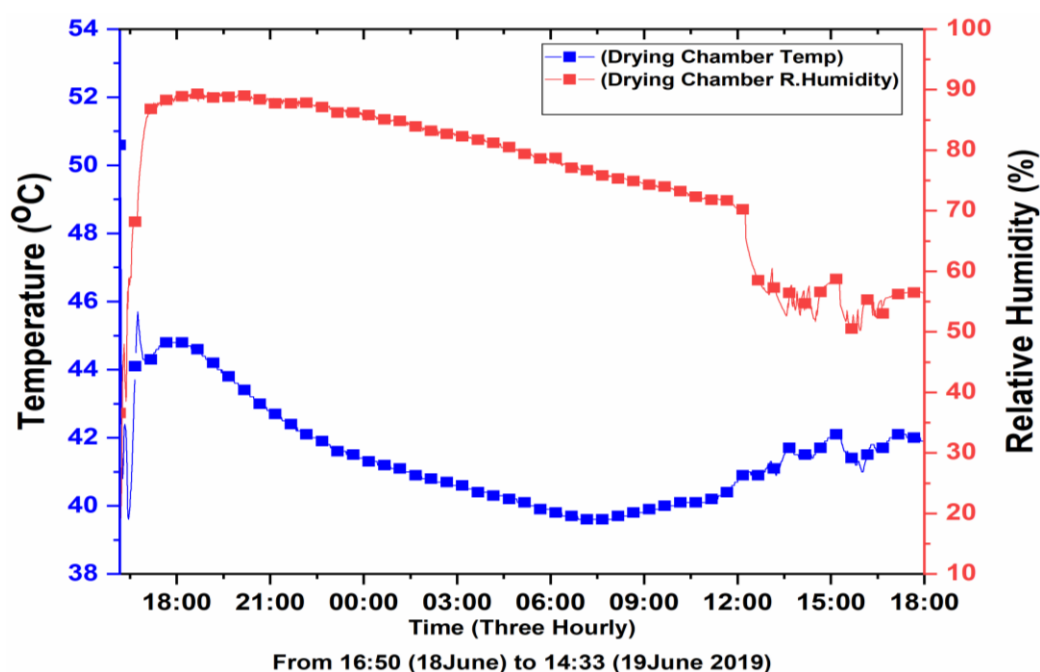


Figure 4.23: DC temperature and relative humidity profile during drying Tests.

The DC temperature and R.H were at 44.2°C and 85.6% respectively, when the doors were closed at 17:07 on 18 June 2019 refer to Figure 4.23. The lowest temperature of 39.6 °C, was attained at 06:54 on 19 June 2019 at R.H. of 76.3% and remained steady at 39.6°C from 06:54 to 08:01 (1hr, 7minutes). During this period, the R.H. reduced from 77% to 75.5%. From 08:01, the temperature gradually increased to an average of 42.2°C while the RH kept on

dropping until it stagnated at an average of 53% for 5 hours when the drying experiment was stopped. The slope in linear fit was, -2.4 ± 0.1 for the DC temperature and -33.2 ± 0.6 DC RH. This indicated that the RH degreased at a much faster rate than the DC temperature.

4.5 COWPEA (KUNDE) DRYING TESTS RESULTS AND ENERGY ANALYSIS

Table 4.13 shows the results of the weights of the cowpea vegetable on the trays.

Table 4.13: Drying tests results

Tray#	M_i (g)	M_f (g) (dry solids)	$ML = (M_i - M_f)$	$MC (\%) = \left(\frac{M_i - M_f}{M_i} \right) \times 100$	Drying time (Hrs)	M_{dr} (g/hr) $= (ML/hr)$
Hot Side (H)						
T1H	2102	320	1782	84.8	18	99
T2H	1760	280	1480	84.1	18	82.2
T3H	1543	283	1260	81.7	18	70
T4H	1268	240	1028	81.1	18	57.1
T5H	1037	120	917	88.4	18	50.9
c Cold side						
T1C	2021	301	1720	85.1	18	95.6
T2C	1861	296	1565	84.1	18	86.9
T3C	2322	407	1915	82.5	18	106.4
T4C	2692	420	2272	84.4	18	126.2
T 5C	2247	294	1953	86.9	18	108.5
Total	18,853	2961	15,892	84.3	18	882.9g/hr

M_i is Initial weight of samples, M_f is Final weight of sample after drying, ML is moisture removed, $MC (\%)$ is moisture content WB, M_{dr} is average drying rate.

The total weight of the blanched cowpea vegetables loaded in the dryer was 18,853grams as shown in Table 4.12. The vegetables were weighed after 18 hours of drying and the total weight (M_f) was 2,961grams. The difference of 15,892 grams was the moisture content (ML) wb. The average moisture content (MC) of the cowpea was 84.3% wb. The average drying

rate (M_{dr}) was 882.9g/hr (0.8829kg/hr) and the overall moisture content dry basis was 5.4 (540%). These is in conformity with Imungi & Potter (1983) and Herforth (2011) who investigated the nutrition values of the cowpea leaves and found total solid content to be between 10 to 14.8% and moisture content dry basis of between 78 to 87 % (Herforth, 2011; Imungi & Potter, 1983).

The drying conditions and duration is in conformity with the required standards to insure the nutrition values and quality maintained in the cowpea leaves. A temperature level of between 40°C to 65°C was achieved and recommended, by (Gogo et al., 2016).

4.5.1 Energy Analysis

Total Energy Consumption

The Energy consumption of the dryer (E_t) in the drying experiment phase was calculated using equation (Equation 3.11) and was 78,969.8 kj (21.9 kWh). The energy responsible for drying 1g or kg of fresh vegetables of water removed (E_m) was obtainable using equation (equation 3.12) and was 4188.7 kj/kg or 4.2 kj/g (1.2 kWh/kg or 0.00122 Kwh/g).

This is comparable to 4220 to 24990 kj/kg of water removed in microwave dryers and 5210 to 90400 Kj/kg in convective dryers, found by (Nwakuba et al., 2016) who investigated energy required to dry sliced agricultural products. The specific energy consumption was 4967 kJ/kg. This is lower than the reported 42520 to 50890 kJ/kg using a gas dryer (Elmesery & Mwithiga, 2012; Nwakuba et al., 2016).

4.5.2 Thermal/Energy Efficiency

The energy efficiency (η)

The energy efficiency was calculated by relating the energy used for moisture evaporation from the vegetables (Kunde) feed temperature (E_{EV}) to the total energy supplied to the dryer (E_t) (Kudra, 2012). It was 84.4%, applying (Equation 3.19).

$E_{ev} = E_m \times \text{weight of water evaporated from Kunde (15.9kg)} = 4188.7 \times 15.9 = 66600.33 \text{ kJ.}$

E_{ev} is the energy used for moisture evaporation.

$$E_{ev} = E_m \times \text{weight of water evaporated} \quad \text{Equation 4.1}$$

The equation used to calculate the dry weight of cowpea was:

$$\text{Dry weight of cowpea (Mf)} = (M_i - M_f) \quad \text{Equation 4.2}$$

M_f was 2961 grams.

Thermal Efficiency

Thermal efficiency (η_t) was calculated according to; based on equation 3.20 and was 62% (Adegbite et al., 2019; Mujumdar, 2015). This is higher than the reported 20 to 60% in convective dryers. Pneumatic dryers reported with the efficiency of 50 to 75 % (Chauhan & Rathod, 2018). This efficiency in the thermophilic dryer can be attributed to the heat recovery and moisture dumping system using the heat sink hole.

4.6 Drying experiment summery

Table 4.14: Drying experiment summary

Parameter	Symbol	Value	Equation Used
Energy for the drying period	E_t	78,969.8 kJ	3.11
Energy used for moisture evaporation	E_{EV}	66,434 kJ	4.1
Energy responsible for drying 1g or kg	E_m	4,188.7 kJ/kg	3.12
Energy to raise Temp. of Cowpea to Air Temp	E_1	1324.4 kJ	3.13
Latent Heat of Vaporization to remove moisture from Cowpea	E_2	38,160	3.13
Energy Lost during drying	Loss	39,485.41 kJ	3.13
Drying system efficiency	η_{system}	49.99%	3.17
Dryer Efficiency	η_d	48.32%	3.18
Energy efficiency	η	84.4 %	3.19
Thermal efficiency	η_t	62 %	3.20
Moisture removed	ML	15,892 g	3.14
Moisture wet weight basis	MC wb	84.3 %	3.14
Drying rate	M_{dr}	882.9 g/hr	3.16
Dry weight of cowpea	M_f	2,961 g	4.2
Moisture dry basis	MC db	5.4 (540 %)	3.15

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The efficacy of applying waste heat from aerobic decomposition of biodegradable farm wastes by thermophilic bacteria, to supplement conventional solar heat to extend drying hours of food, to prevent post-harvest spoilage and contamination with harmful mycotoxins and aflatoxins in Kitale, Trans-Nzoia County in Kenya, has been demonstrated in this study. The availability of more than 22,000 ton/day of wastes of which 60 % are organic, compostable, rural and agricultural generated, poses a challenge to waste management in the country, but gives an opportunity as a source of feedstocks to this technology.

It has been deduced in this study and others, that designing an aerobic Composition Heat Recovery System (CHRS) is complex and include external factors such as; climatic conditions (weather, season of the year), environment, thermal insulation and internal factors such as; energy and nutrient content of the feedstock matrix, degradability and porosity. Knowing the feedstock chemical and physical characteristics is important and is site and feedstock specific. Through specific objective number one, optimal operating ranges of the feedstocks to create, enabling conditions for microbial activities were established after characterization. The optimum conditions e.g.; C/N ratio of 28.8:1, pH of 6.8 and moisture content of 57.7 % were applied. Therefore, the compost feedstock matrix operated within the optimum range. The matured compost manure stabilized, with the macro and micronutrients important for soil amendments, was the by-product that can be used to improve soil quality.

The conclusion has been drawn, from these study that, results from specific objective number one were used to develop and construct a 1350.2 kg wb, surface area-to-volume ratio of $4.4[\text{m}^2/\text{m}^3]$ standalone and static aerated compost reactor with a 36 liters or 36 kg of water within pile compost heat extractor (COHE). The pump flow rate was 0.025 L/s. All materials used to fabricate the systems were locally sourced. The dryer was a 9.45 m^2 area and 2.05 m^3 volume chamber capacity with ten horizontal drying trays. It had a 0.004m thick glass solar collector on top and a 3.6 m^2 area and 0.33 m^3 volume heat absorption chamber (HAC). The HAC inter-changed the roles depending on the tests been taken. During solar only test, it worked as air heat absorber and during hybrid tests as a hot water tank (240 kg of water).

Specific objective number three was to test and evaluate the system by profiling of energy and drying performance using temperature and humidity data loggers mounted at different locations within the compost reactor and the dehydration chamber. Data analysis achieved, using the Origin Pro 2018 graphing analysis software.

The Control test (Electrical and solar) provided the basis to compare the tests that were conducted. It has been deduced that with this type of encased drying system, the electrical energy required to heat the drying chamber to temperatures between 40°C to 60°C is low as compared to other dryers. The compost reactor attained a 62.7°C mean temperature, maximum of 68.9°C and generated energy increased from a low of 106 MJ to a peak 286 MJ during its 36 days lifetime. The total extracted energy by the COHE in 205 hours was 727 MJ (174 kWh). The coefficient of Performance (COP) of the Compost Heat Extractor attained a mean of 74.22 and maximum of 489.9 and attributed to the low energy consumption of the system auxiliary equipment. These resulted into the drying chamber

temperatures of 40 to 60 °C at humidity of 40 to 65 %, therefore providing optimal conditions for low temperature drying.

Cowpea (*Vigna unguiculata*) vegetables leaves dried from a moisture content of 84.3 %wb to 15.7 %wb within 18 hours, and with thermal efficiency of 62 % comparable to other drying technologies. Hence, the results affirm the efficacy of food drying with heat from composting of farm wastes. The hybrid solar-thermophilic dryer promises to be a sustainable and may be a cost-effective renewable energy solution to mitigating post-harvest losses on farms in Africa. The energy could be generated, from local sources of organic matter in its operation and has a double benefit of returning the mature compost to the local soils. This is advantageous to the agriculture sector by creating healthy soils that otherwise could have been degraded by using artificial fertilizers. The 174 kWh generated substituted 48 kgCO₂/kWh of CO₂ emissions generated by diesel generators. This research answers to SDG # 7 “Renewable and clean Energy.” Facilitation of access to clean energy research is a key component to this goal.

5.2 RECOMMENDATIONS

Further work on compost heat exchanger model optimization, in relation to dryer sizing, to improve the efficiency, is recommended. The optimization of heat extraction system, while not affecting, the behavior of the microorganisms, could be done. Analysis of the thermal conductivity of the materials for the compost heat extractor is important to ensure the reduction in pressure drops in the heat exchanger. Furthermore, the sizing of the solar component and the heat sink hole should further be research to achieve the maximum energy savings from the system. The economic and cost analysis of manufacturing an easy to operate

system, operated by unskilled labor is eminent to maximize the utilization of the hybrid solar thermophilic heat collector.

REFERENCES

- A &L, (A&L Great Lakes Laboratories). (2018). *Compost Analysis. The U.S. Composting Council*. Retrieved from <https://algreatlakes.com/pages/compost-analysis>
- Abasi, S., Minaee, S., & Khoshtaghaza, H. (2016). Drying Technology : An International Journal Performance of a Recirculating Dryer Equipped with a Desiccant Wheel. *Taylor & Francis*, 34(8), 863–870. <https://doi.org/10.1080/07373937.2015.1021421>
- Adams, Z. (2005). Understanding Biothrmal Energy. *University of Vermont*, 128. Retrieved from <https://www.scribd.com/document/326833248/Understanding-Biothermal-Energy-Zak-Adams-THESIS-MSc-at-UVM>
- Adegbite, S. A., Adebayo, A., Olukunle, O. J., Olalusi, A. P., Asiru, W. B., & Awoyale, W. (2019). Mass and Energy Balance Analysis of Pneumatic Dryers for Cassava and Development of Optimization Models to Increase Competitiveness in Nigeria. *Current Journal of Applied Science and Technology*, 32(3), 1–11. <https://doi.org/10.9734/CJAST/2019/46215>
- Aissa, W., El-Sallak, M., & Elhakem, A. (2014). Performance of solar dryer chamber used for convective drying of sponge-cotton. *Thermal Science*, 18(SUPPL.2), 451–462. <https://doi.org/10.2298/TSCI110710084A>
- Al-neama, M., & Farkas, I. (2018). Utilization of Solar Air Collectors for Product ' s Drying Processes. *Journal of Scientific and Engineering Research*, 5(2), 40–56. Retrieved from https://www.researchgate.net/publication/326803939_Utilization_of_Solar_Air_Collectors_for_Product's_Drying_Processes
- Allen, B., & Chambers, P. D. (2009). *The Design and Development of Heat Extraction Technologies for the Utilization of Compost Thermal Energy*. Galway Mayo Institute of Technology. Retrieved from https://research.thea.ie/bitstream/handle/20.500.12065/369/Donal_P_Chambers_2013_0916094330.pdf?sequence=1&isAllowed=y
- Amer, B. M. A., Hossain, M. A., & Gottschalk, K. (2010). Design and performance evaluation of a new hybrid solar dryer for banana. *Energy Conversion and Management*, 51(4), 813–820. <https://doi.org/10.1016/j.enconman.2009.11.016>
- Anderson, K. R., Salem, Y., Shihadeh, S., Perez, P., Kampen, B., Jouhar, S., ... Wang, K. (2016). Design of a Compost Waste Heat to Energy Solar Chimney Power Plant. *Journal of Civil Engineering Research* 2016, 6(3), 47–54. <https://doi.org/10.5923/j.jce.20160603.01>
- Anderson, K. R., Shafahi, M., & McNamara, C. (2015). Thermal-Fluids Analysis of a Hybrid Solar/Compost Waste Heat Updraft Tower. *Journal of Clean Energy Technologies*, 4(3), 213–220. <https://doi.org/10.7763/jocet.2016.v4.283>

- Antil, R. S., Janssen, B. H., & Lantinga, E. A. (2009). Laboratory and greenhouse assessment of plant availability of organic N in animal manure. *Nutrient Cycling in Agroecosystems*, 85(1), 95–106. <https://doi.org/10.1007/s10705-009-9251-1>
- Ayre, L. (2002). *Making Great Compost to Grow Great Vegetables*. *Mycological Research* (Vol. 106). Retrieved from <https://www.vegetable-gardening-with-lorraine.com/homemade-compost-bin.html>
- Bajko, J., Fišer, J., & Jícha, M. (2018). Temperature measurement and performance assessment of the experimental composting bioreactor. In *EPJ Web of Conferences* (Vol. 180, p. 02003). EDP Sciences. <https://doi.org/10.1051/epjconf/201818002003>
- Bajko, J., Fišer, J., & Jícha, M. (2019). Condenser-Type Heat Exchanger for Compost Heat Recovery Systems. *Energies*, 12(8), 1583. <https://doi.org/10.3390/en12081583>
- BCMAF, (British Columbia Ministry of Agriculture and Food). BC Agricultural Composting Handbook - BC Ministry of Agriculture, 3100 § (1998). Canada. Retrieved from <https://en.calameo.com/books/0016403728bbedf389e97>
- Behera, D., & Das, S. S. (2019). Design and fabrication of Forced Convection Cabinet type of solar dryer for drying fruits and vegetables. *International Journal of Management, Technology And Engineering*, (May), 2249–7455. Retrieved from https://www.researchgate.net/publication/333184733_Design_and_fabrication_of_Forced_Convection_Cabinet_type_of_solar_dryer_for_drying_fruits_and_vegetables
- Brandl, H. (2013). Thermo-Active Ground-Source Structures for Heating and Cooling. *Procedia Engineering*, 57, 9–18. <https://doi.org/10.1016/j.proeng.2013.04.005>
- Chauhan, Y. B., & Rathod, P. P. (2018). A Comprehensive Review on Solar Dryer. *International Journal of Ambient Energy*, 41(3), 348–367. <https://doi.org/10.1080/01430750.2018.1456960>
- Christian, A., Evanylo, K. G., Pease, W. J., Evanylo, G. K., & Pease, J. W. (2009). *On Farm Composting A Guide to Principals, Planning and Operations*. (V. S. University, Ed.), *ResearchGate*. Virginia: Virginia Cooperative Extension. Retrieved from https://www.researchgate.net/publication/237698064_ON_FARM_COMPOSTING_A_GUIDE_TO_PRINCIPLES_PLANNING_AND_OPERATIONS
- Czajkowski, Ł., Wojcieszak, D., Olek, W., & Przybył, J. (2019). Thermal properties of fractions of corn stover. *Construction and Building Materials*, 210, 709–712. <https://doi.org/10.1016/j.conbuildmat.2019.03.092>
- Diabaté, L., Blanc, P., & Wald, L. (2004). Solar radiation climate in Africa. *Solar Energy*, 76(6), 733–744. <https://doi.org/10.1016/j.solener.2004.01.002>
- Drosg, B., Braun, R., Bochmann, G., & Al Saedi, T. (2013). Analysis and characterisation of biogas feedstocks. In *The Biogas Handbook: Science, Production and Applications* (pp.

- 52–84). Elsevier Inc. <https://doi.org/10.1533/9780857097415.1.52>
- Earthscan. (2010). *Planning & Installing Solar Thermal Systems* (Second). London: earth scan, London, Washington, DC. Retrieved from https://energiarenovablenec.files.wordpress.com/2015/08/german_solar_energy_society_dgs_planning_and_ibookzz-org.pdf
- Ekechukwu, V., & Norton, B. (1999). Review of solar energy drying systems , II : An overview of solar drying technology Review of solar-energy drying systems III : low temperature air-heating solar collectors for crop drying applications. *Energy Conversion & Management*, 8904(December 2015), 657–667. [https://doi.org/10.1016/S0196-8904\(98\)00093-4](https://doi.org/10.1016/S0196-8904(98)00093-4)
- Ekinci, K. (2001). *Theoretical and Experimental studies on the Effects of Aeration Strategies on the Composting Process*. The Ohio State University. Retrieved from https://books.google.co.ke/books/about/Theoretical_and_Experimental_Studies_on.html?id=mWQLtwAACAAJ&redir_esc=y
- El-mesery, H. S., & Mwithiga, G. (2012). Comparison of a Gas Fired Hot-Air Dryer with an Electrically Heated Hot-Air Dryer in terms of Drying Process, Energy Consumption and Quality of Dried Onion Slices. *African Journal of Agricultural Research*, 7(31), 4440–4452. <https://doi.org/10.5897/AJAR12.614>
- Epstein, E. (2011). *Industrial composting: Environmental Engineering and Facilities Management*. London: Taylor & Francis Group. <https://doi.org/https://doi.org/10.1201/b10726>
- Esbensen, K., Julius, L. P., Holm-Nielsen, J. B., Mortensen, P. P., & Friis-Petersen, hans H. (2007). Representative Process Sampling - in practice: Variographic Analysis and Estimation of Total Sampling errors (TSE). *Chemometrics and Intelligent Laboratory Systems-Elsevier*, 88(1), 41–59. <https://doi.org/10.1016/j.chemolab.2006.09.011>
- FAO, (Food Agriculture organization). (2018). *Food loss analysis : causes and solutions*. Rome. Retrieved from <http://www.fao.org/3/BU676EN/bu676en.pdf>
- FAO, IFAD, UNICEF, WFP, & WHO. (2017). *The State of Food Security and Nutrition in the World. Fao*. Retrieved from <http://www.fao.org/3/a-i7695e.pdf>
- Finstein, M. S., Miller, F. C., & Strom, P. F. (1986). Monitoring and Evaluating Compostin Process Performance. *Journal (Water Pollution Control Federation)*, 58(4), 272–278. Retrieved from <https://www.jstor.org/stable/25042902>
- Fudholi, A., Othman, M. Y., Ruslan, M. H., Yahya, M., Zaharim, A., & Sopian, K. (2011). The Effects of Drying Air Temperature and Humidity on the Drying Kinetics of Seaweed. In *4th WSEAS international conference on Energy and development - environment - biomedicine* (pp. 129–133).

- G. Irvine, E. R. Lamont, & B. Antizar-Ladislao. (2010, April). Energy from Waste: Reuse of Compost Heat as a Source of Renewable Energy. <https://doi.org/10.1155/2010/627930>
- Garden-Robinson, J. (2017). Drying Vegetables. *North Dakota State University Extension Service*, 1–4. Retrieved from <https://www.ag.ndsu.edu/publications/food-nutrition/drying-vegetables/fn1588.pdf>
- Gogo, E., Apiyo, A., Ulrichs, C. &, & Huyskens-Keil, S. (2016). POSTHARVEST TREATMENTS OF AFRICAN LEAFY VEGETABLES FOR FOOD SECURITY IN KENYA: A REVIEW. Retrieved from <http://www.hakenya.net/ajhs/index.php/ajhs/article/view/153>
- Gómez, C. (2003). Cowpea Post-Harvest Operations in Developing Countries by : Retrieved from <http://www.fao.org/3/a-au994e.pdf>
- Green, M. G., & Schwarz, D. (2014). Solar Drying Technology for Food Preservation. Retrieved from https://www.researchgate.net/publication/237503256_Solar_Drying_Technology_for_Food_Preservation
- Haug, R. T. (1993). *The Practical Handbook of Compost Engineering*. (T. and Francis, Ed.). New York: Lewis Publishers. Retrieved from https://books.google.co.ke/books/about/The_Practical_Handbook_of_Compost_Engine.html?id=MX_jbemODmAC&redir_esc=y
- Hegde, V. N., Hosur, V. S., Rathod, S. K., Harsoor, P. A., & Narayana, K. B. (2015). Design, Fabrication and Performance Evaluation of Solar Dryer for Banana. *Energy, Sustainability and Society*, 5(1). <https://doi.org/10.1186/s13705-015-0052-x>
- Herforth, A. W. (2011). *Promotion of traditional African vegetables in Kenya and Tanzania: A case study of an intervention representing emerging imperatives in global nutrition. Dissertation Abstracts International, B: Sciences and Engineering*. Cornell. Retrieved from https://farmconcern.org/images/Newsletters/AnnaHerforth_PhDthesis.pdf
- Holman, J. P. (2012). *Experimental Methods for Engineers* (Eighth Edi). McGraw-Hill: The McGraw Hill Companies. Retrieved from https://www.academia.edu/37092938/Experimental_Methods_for_Engineers_Eighth_Edition
- Hossain, M. A., Amer, M. B., & Gottschalk, K. (2009). Hybrid Solar Dryer for Quality Dried Tomato. *Drying Technology*, 26(December 2013), 1591–1601. <https://doi.org/10.1080/07373930802467466>
- Hughes, D. F. (1984). Extraction of energy from an aerobic farm waste lagoon. *Journal of Agricultural Engineering Research*, 29(2), 133–139. [https://doi.org/10.1016/0021-8634\(84\)90067-2](https://doi.org/10.1016/0021-8634(84)90067-2)

- Imungi, K. K., & Potter, N. N. (1983). Nutrient Contents of Raw and Cooked Cowpea Leaves. *Journal of Food Science*, 48, 1252–1254. <https://doi.org/10.1111/j.1365-2621.1983.tb09204.x>
- Irvine, G., Lamont, E. R., & Antizar-Ladislao, B. (2014). Energy from Waste : Reuse of Compost Heat as a Source of Renewable Energy Energy from Waste : Reuse of Compost Heat as a Source of Renewable Energy. *International Journal of Chemical Engineering*, 2010(May), 12. <https://doi.org/10.1155/2010/627930>
- Jindal, R., & Ratanamalaya, P. (2006). Modeling of Heat Generation in an Aerobic Composting Process. In *The 2nd Joint International Conference on "Sustainable Energy and Environment* (Vol. 075, pp. 1–7). Bangkok. Retrieved from <https://www.yumpu.com/en/document/view/29763934/modeling-of-heat-generation-in-an-aerobic-composting-process>
- Kabenge, I., Omulo, G., Banadda, N., Seay, J., Zziwa, A., & Kiggundu, N. (2018). Characterization of Banana Peels Wastes as Potential Slow Pyrolysis Feedstock. *Journal of Sustainable Development*, 11(2), 14. <https://doi.org/10.5539/jsd.v11n2p14>
- Kalogirou, S. A. (2018). Industrial Process Heat , Chemistry Ap- plications , and Solar Dryers. In *Solar Energy Engineering*. Academic Press. <https://doi.org/10.1016/B978-0-12-397270-5.00007-8>
- Keener, H. M., Ekinici, K., Elwell, D. L., & Michel, Jr, F. C. (1991). Principles of Composting Process Optimization. Retrieved from <https://www.tandfonline.com/doi/ref/10.1080/1065657X.2005.10702253?scroll=top>
- Keener, H. M., Elwell, D. L., Das, K., & Hansen, R. C. (1996). Remix Scheduling During Composting Based on Moisture Control. *American Society of Agricultural Engineers*, 39(1988), 1839–1845. <https://doi.org/10.13031/2013.27661>
- Keener, H. M., Hansen, R. C., & Elwell, D. L. (1997). Airflow Through Compost: Design and Cost Implications. *Applied Engineering in Agriculture*, 13(3), 377–384. <https://doi.org/10.13031/2013.21613>
- Kemp, I. C. (2014). Fundamentals of Energy Analysis of Dryers. *Modern Drying Technology*, 4–4, 1–45. <https://doi.org/10.1002/9783527631681.ch1>
- Khoukhi, M., & Maruyama, S. (2006). Theoretical approach of a flat-plate solar collector taking into account the absorption and emission within glass cover layer. *Solar Energy*, 80(7), 787–794. <https://doi.org/10.1016/j.solener.2005.06.002>
- Kiremire, B. T., Musinguzi, E., Kikafunda, J. K., & Lukwago, F. B. (2010). Effects of Vegetable Drying Techniques on Nutrient Content: a Case Study of South-Western Uganda. *African Journal of Food, Agriculture, Nutrition and Development*, 10(5), 2587–2600. <https://doi.org/10.4314/ajfand.v10i5.56341>

- Koyuncu, T., Pinar, Y., & Lule, F. (2007). Convective Drying Characteristics of Azarole red (*Crataegus Monogyna* Jacq .) and Yellow (*Crataegus Aronia* Bosc .) Fruits. *Journal of Food Engineering-Elsevier*, 78, 1471–1475. <https://doi.org/10.1016/j.jfoodeng.2005.09.036>
- Kudra, T. (2012). Energy Performance of Convective Dryers. *Drying Technology An International Journal*, 30(11–12), 1190–1198. <https://doi.org/10.1080/07373937.2012.690803>
- María, J., Jarquín, H., Diaz, J. E., Patel, K. R., Gomez, G. P., Castillo, E. A. M., & Diaz, R. I. (2018). Construction and Evaluation of Solar Thermal-Wind Hybrid Dryer for Food Processing in Chiapas, Mx. Retrieved from http://www.consolfood.org/wp-content/uploads/2018/02/posters/P12_Jarquín-Patel.pdf
- Marinescu, M., Volpe, S., Descrochers, L., & Roser, D. (2015). Basic Procedures for Sampling and Analyzing Woody Biomass. Retrieved from <https://www.researchgate.net/publication/280023052%0D>
- Mason, I. G., & Milke, M. W. (2005). Physical Modelling of the Composting Environment : A Review . Part 1 : Reactor Systems. *Waste Management-Elsevier*, 25, 481–500. <https://doi.org/10.1016/j.wasman.2005.01.015>
- Mbaka, J. G., & Mwaniki, M. (2016). Small Hydro-power Plants in Kenya : A Review of Status , Challenges and Future Prospects. Retrieved from <https://www.researchgate.net/publication/319877260>
- MEF, (Ministry of Environment and Forestry). National Sustainable Waste Management Policy (2019). Ministry of Environment and Forestry of Kenya. Retrieved from http://www.environment.go.ke/wp-content/uploads/2019/05/Revised_National_Waste_Policy5_2019.pdf
- Misha, S., Sohif, M., Ruslan, M. H., & Soplan, B. K. (2013). The Effect of Drying Air Temperature and Humidity on the Drying Kinetic of Kenaf Core, (March). <https://doi.org/10.4028/www.scientific.net/AMM.315.710>
- Mohee, R. (2007). *Waste Management Opportunities for Rural Communities. Food and Agriculture Organization of the United Nations*. Retrieved from <http://www.fao.org/3/k1455e/k1455e.pdf>
- Mujumdar, A. S. (2015). *Handbook of Industrial Drying. Handbook of Industrial Drying Technology* (Fourth). London: Taylor & Francis Group. <https://doi.org/10.1080/07373930701399224>
- Mumba, J. (1995). Development of a Photovoltaic Powered Forced Circulation grain Dryer for use in the Tropics. *Pergamon*, 6(7), 855–862. [https://doi.org/10.1016/0960-1481\(94\)00088-N](https://doi.org/10.1016/0960-1481(94)00088-N)

- Mutali, G., & Mbugu, D. O. (2015). Drying Characteristics and Energy Requirement of Drying Cowpea Leaves and Jute Mallow Vegetables. Retrieved from <https://cigrjournal.org/index.php/Ejournal/article/view/3368>
- Mutegi, C. K., Cotty, P. J., & Bandyopadhyay, R. (2018). Prevalence and Mitigation of Aflatoxins in Kenya (1960-to date). *World Mycotoxin Journal*, 11(3), 341–357. <https://doi.org/10.3920/WMJ2018.2362>
- Natabirwa, H., Mukiibi, J., Zziwa, E., & Kabirizi, J. (2017). Nutritional and Physicochemical Properties of Stored Solar-Dried Cowpea Leafy Vegetables. *Uganda Journal of Agricultural Sciences*, 17(1), 1. <https://doi.org/10.4314/uja.v17i1.1>
- Neugebauer, M., Sołowiej, P., & Piechocki, J. (2014). Fuzzy Control for the Process of Heat Removal During the Composting of Agricultural Waste. *Journal of Material Cycles and Waste Management*, 16(2), 291–297. <https://doi.org/10.1007/s10163-013-0188-8>
- Nwakuba, N. R., Asoegwu, S. N., & Nwaigwe, K. N. (2016). Energy Requirements for Drying of Sliced Agricultural Products: A Review. Retrieved from <https://www.researchgate.net/publication/304771464>
- OME, (Ontario Ministry of the Environment). (2012). Ontario Compost Quality Standards. Retrieved from <https://www.ontario.ca/page/ontario-compost-quality-standards#:~:text=The Standards set out three,use as a soil conditioner>
- Panchal, H., & Mohan, I. (2017). Various Methods Applied to Solar still for Enhancement of Distillate Output. *Desalination*, 415(April), 76–89. <https://doi.org/10.1016/j.desal.2017.04.015>
- Pellaton, A. (1972). The Methods of Jean Pain. Retrieved from https://archive.org/details/Another_Kind_of_Garden-The_Methods_of_Jean_Pain
- Peters, J., Combs, S. M., Hoskins, B., Jarman, J., Kovar, J. L., Watson, M. E., ... Wolf, N. (2003). Recommended Methods of Manure Analysis. Retrieved from <https://cdn.shopify.com/s/files/1/0145/8808/4272/files/A3769.pdf>
- Phillip, E. A. (2010). The Design and Construction of a Pilot-Scale Compost Reactor for the Study of Gas Emissions from Compost under Different Physical Conditions. Retrieved from <https://escholarship.mcgill.ca/concern/theses/b5644s009>
- Pitschel, K., & Lowry, E. (2016). Gibbs House Compost Heat Recovery System. Retrieved from <https://wmich.edu/sites/default/files/attachments/u691/2016/LowryPitschel1.pdf>
- PT, (Pico Technology). (2019). *TC-08 8-channel thermocouple data logger*. Retrieved from www.picotech.com/downloads%0ACompatible
- Raji, A. O., & Olanrewaju, T. O. (2015). Effect of Period of Harvest on Drying Characteristics of an Improved Variety Cowpea (IT 97K-56S-IS). Retrieved from

<https://cigrjournal.org/index.php/Ejournal/article/view/3385>

- Rynk, R., Kamp, aarten van de, Willson, G., Singley, M. E., Richard, T. L., & Kolega, J. J. (1992). On-Farm Composting Handbook. Retrieved from NRAES-054.pdf (73.97Mb)
- Sagar, V. R., & Kumar, S. P. (2010). Recent Advances in Drying and Dehydration of Fruits and Vegetables: A review. *Journal of Food Science and Technology*, 47(1), 15–26. <https://doi.org/10.1007/s13197-010-0010-8>
- Seki, H., & Komori, T. (1987). A Theoretical Investigation of Heat Extraction from a Compost by Using a Multi-Heat-Pipe Heat Exchanger. Retrieved from https://www.jstage.jst.go.jp/article/agrmet1943/42/4/42_4_337/_pdf/-char/ja
- Shimizu, N. (2017). Process Optimization of Composting Systems. In *Robotics and Mechatronics for Agriculture* (p. 23). Hokkaido: CRC Press. <https://doi.org/10.1201/9781315203638-1>
- Shimizu, N., Nugroho, J., Karyadi, W., Harano, M., Iwabuchi, K., & Kimura, T. (2018). Cattle Manure Composting in a Packed-Bed Reactor with Forced Aeration Strategy. *Engineering in Agriculture, Environment and Food*, 42. <https://doi.org/10.1016/j.eaef.2018.01.002>
- Smith, M. M. . M., & Aber, J. D. (2018). Energy recovery from commercial-scale composting as a novel waste management strategy. *Applied Energy*, 211(October 2017), 194–199. <https://doi.org/10.1016/j.apenergy.2017.11.006>
- Smith, M. M., & Aber, J. D. (2014). Heat Recovery from Compost: A Guid to Building an Aerated Static Pile Heat Recovery Composting Facility. Retrieved from <http://nswai.com/docs/Heat Recovery from Compost.pdf>
- Smith, M. M., Aber, J. D., & Rynk, R. (2017). Heat Recovery from Composting: A Comprehensive Review of System Design, Recovery Rate, and Utilization. *Compost Science and Utilization*, 25(1), S11–S22. <https://doi.org/https://doi.org/10.1080/1065657X.2016.1233082>
- Spröte, W. (2019). UN-ECOSOC – Economic And Social Council. Retrieved from <https://undocs.org/en/A/RES/70/1>
- Sutitarnnontr, P., Hu, E., Tuller, M., & Jones, S. B. (2014). Physical and thermal characteristics of dairy cattle manure. *Journal of Environmental Quality*, 43(6), 2115–2129. <https://doi.org/10.2134/jeq2014.05.0212>
- Svoboda, I. F., & Fallowfield, H. J. (1989). *An aerobic piggery slurry treatment system with integrated heat recovery and high-rate algal ponds*. *Water Science and Technology* (Vol. 21). International Association on Water Pollution Research and Control. <https://doi.org/10.2166/wst.1989.0230>

- Twidell, J., & Weir, T. (2006). *Renewable Energy Resources*. (A. D. W. John W. Twidell, Ed.) (second). New York: Taylor & Francis.
- UNFPA. (2014). Kenya - Population. *Unfpa*, 3–5. Retrieved from <http://countryeconomy.com/demography/population/kenya>
- Wagacha, J. M., Steiner, U., Dehne, H. W., Zuehlke, S., Spiteller, M., Muthomi, J., & Oerke, E. C. (2010). Diversity in Mycotoxins and Fungal Species Infecting Wheat in Nakuru District, Kenya. *Journal of Phytopathology*, 158(7–8), 527–535. <https://doi.org/10.1111/j.1439-0434.2009.01653.x>
- Wang, S., Jiang, X. M., Wang, Q., Ji, H. S., Wu, L. F., Wang, J. F., & Xu, S. N. (2014). Research of specific heat capacities of three large seaweed biomass. *Journal of Thermal Analysis and Calorimetry*, 115(3), 2071–2077. <https://doi.org/10.1007/s10973-013-3141-0>
- Wang, X., Lu, X., Li, F., & Yang, G. (2014). Effects of Temperature and Carbon-Nitrogen (C/N) ratio on the Performance of Anaerobic Co-digestion of Dairy Manure, Chicken Manure and rice straw: Focusing on ammonia inhibition. *PLoS ONE*, 9(5), 1–7. <https://doi.org/10.1371/journal.pone.0097265>
- Wright, R. J. (1998). Agricultural Uses of Municipal, Animal, and Industrial Byproducts. Retrieved from <https://www.ars.usda.gov/is/np/agbyproducts/agbychap1.pdf>
- Zhong, H., Li, Z., Wu, T., Yu, M., & Tang, R. (2012). Performance of a Solar Drying System Driven by a Hybrid Power System. *Advanced Materials Research*, 455–456(September), 139–146. <https://doi.org/10.4028/www.scientific.net/AMR.455-456.139>

APPENDICES

Appendix A.: Rice Straw burning in a field in Philippines



Appendix B: Open sun drying of Rice



Appendix C: Open maize drying in Kitale, Kenya



Appendix D: Characterization results from KALRO



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MANURE ANALYSIS REPORT

Name	Mwape Chikonkolo Mwewa
Address	Moi University, Eldoret
Location	Kitale, Trans-Nzoia
Date sample received	1-Jul-19
Date sample reported	12-Jul-19
Reporting officer (through Director NARL)	A. Chek

Analytical data (Test results)						
Sample description	4 A/B	5	6	7 A/B	8 A/B	10
Lab No/2019	4816	4817	4818	4819	4820	4821
pH (1:10)	7.95	9.49	9.74	8.78	6.39	9.10
Total Organic Carbon %	49.0	19.7	32.4	36.8	46.5	20.6
Nitrogen %	0.47	0.82	1.40	1.75	0.47	1.28
Phosphorus %	0.18	0.29	0.41	0.60	0.14	0.57
Potassium %	1.42	1.28	1.83	2.40	0.32	2.22
Calcium %	0.02	0.05	0.05	0.17	0.15	0.03
Magnesium %	0.06	0.11	0.12	0.40	0.05	0.17
Iron mg/kg	1862	5050	6733	1983	390	9684
Copper mg/kg	18.3	30.0	48.3	60.0	3.33	93.3
Manganese mg/kg	73.3	463	347	242	157	863
Zinc mg/kg	18.3	170	138	333	1.67	168

Interpretation of analytical data

Results forwarded.

NOTE: Test results are based on customer sampled sample(s).

Appendix E: Linear Fit For the Drying Chamber and Heat Sink Relative Humidity

Linear Fit (07/11/2019 01:20:40)

Parameters

		Value	Standard Error	t-Value	Prob> t
Drying Chamber	Intercept	46.30372	0.40496	114.34135	0
	Slope	0.00356	1.31234E-4	27.14538	0
Heat sink	Intercept	71.4081	0.13932	512.54175	0
	Slope	0.00133	4.51493E-5	29.48007	0

Drying Chamber: Slope is significantly different from zero (See ANOVA Table).

Heat sink: Slope is significantly different from zero (See ANOVA Table).

Standard Error was scaled with square root of reduced Chi-Sqr.

Statistics

	Drying Chamber	Heat sink
Number of Points	5344	5344
Degrees of Freedom	5342	5342
Residual Sum of Squares	1.17007E6	138492.06546
Pearson's r	0.34816	0.37406
R-Square (COD)	0.12122	0.13992
Adj. R-Square	0.12105	0.13976

Summary

	Intercept		Slope		Statistics
	Value	Standard Error	Value	Standard Error	Adj. R-Square
Drying Chamber	46.30372	0.40496	0.00356	1.31234E-4	0.12105
Heat sink	71.4081	0.13932	0.00133	4.51493E-5	0.13976

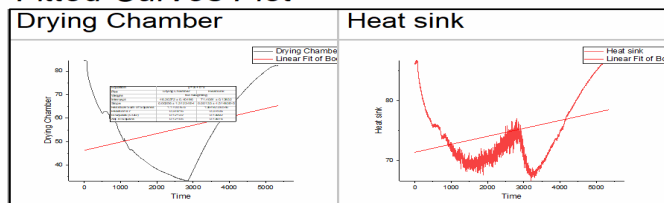
ANOVA

		DF	Sum of Squares	Mean Square	F Value	Prob>F
Drying Chamber	Model	1	161399.28467	161399.28467	736.87171	0
	Error	5342	1.17007E6	219.03309		
	Total	5343	1.33147E6			
Heat sink	Model	1	22530.8777	22530.8777	869.07469	0
	Error	5342	138492.06546	25.92513		
	Total	5343	161022.94316			

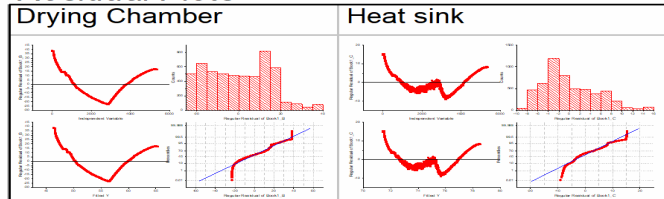
Drying Chamber: At the 0.05 level, the slope is significantly different from zero.

Heat sink: At the 0.05 level, the slope is significantly different from zero.

Fitted Curves Plot



Residual Plots



Appendix F: Research License (NACOSTI-KENYA)

THIS IS TO CERTIFY THAT: MR. CHIKONKOLO MWEWA MWAPE of MOI UNIVERSITY, Zesco Limited, P.O Box 33304-10101 Lusaka, has been permitted to conduct research in Uasin-Gishu County on the topic: EMPOWERING JUA KALI TO COMBAT MYCOTOXINS IN KENYA'S MAIZE SUPPLIES: A PARTICIPATORY DESIGN APPROACH WITH TRANSDISCIPLINARY KNOWLEDGE INTEGRATION for the period ending: 14th December, 2019 <i>[Signature]</i> Applicant's Signature	Permit No : NACOSTI/P/18/99643/27086 Date Of Issue : 14th December, 2018 Fee Received :Ksh 2000 <i>[Signature]</i> Director General National Commission for Science, Technology & Innovation
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