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TITTLE: Determination of optimum mixture of tea waste and sawdust for gasification as a source of energy for tea factory: A case of Itona Tea Factory

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DETERMINATION OF OPTIMUM MIXTURE OF TEA WASTE AND SAWDUST FOR GASIFICATION AS A SOURCE OF ENERGY FOR TEA FACTORY: THE CASE OF ITONA TEA FACTORY

By

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A dissertation submitted in fulfilment of the requirements for the degree of master of Engineering (Clean Energy Technology) of the Mbeya University of Science and Technology

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CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the Mbeya University of Science and Technology a dissertation entitled **Determination of optimum mixture of tea waste and sawdust for gasification as a source of energy for tea factory,** in partial fulfilment of the requirements for the degree of Master of Engineering (Clean Energy Technology) of Mbeya University of Science and Technology.

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Date: ………………………….

DECLARATION AND COPYRIGHT

I, **Andrew Mwampulo**, declare that this dissertation is my own original work and that it has not been presented and will not be presented to any other Institution for a similarly or any other degree award.

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DEDICATION

This work is dedicated to my parents, my beloved wife Joyce, and my daughters, Diana and Gladness, in recognition of their love and gratitude for their support and selflessness during my academic journey.

ABSTRACT

Processing tea requires a lot of energy. However, only significant energy inputs particularly those from fossil fuels, wood fuel, and electricity have been able to support high agricultural productivities and, in turn, the expansion of the green revolution. Due to the recent increase in price and scarcity of these fuels, there has been a shift in the usage of alternative energy sources, such as waste (specifically, agricultural waste), which has the potential to address concerns related to both the environment and energy issues. Moreover, these energy resources have not been able to provide an economically viable solution for agricultural applications even if they seem to contain amount of energy which can be source of energy to be used in various factories in rural areas through gasification process. This study presents an experimental assessment of energy potentials from tea wastes and saw dust available at Itona Tea Factory for tea drying processes as important data for agricultural wastes. The experimental measurement of energy potential from tea wastes was done using bomb calorimeter, muffle furnace and energy balances to determine calorific value, moisture content and energy potentials of tea waste and saw dust respectively. According to the findings, there is sufficient electrical energy for the tea drying process in the tea processing plant, with a total energy potential of $2.78\text{x}10^8$kWh. In order to process 9.6 million kg of tea from a 4.5-thousand-hectare tea plantation in Mufindi (during 2021–2022), the total energy usage (4.5 kWh/kg of produced tea) was 4.32x107 kWh. Gasification of these wastes could provide the energy needed to process tea while reducing the environmental harm caused by burning wood fuel and disposing of waste.

Table of contents

LIST OF TABLES

LIST OF FIGURES

LIST OF ABREVIATION

DDFB	Downdraft Fixed Bed gasifier
UDFB	Updraft Fixed Bed gasifier
FB	Fluidized Bed Gasifier
CFB	Circulating Fluidized Bed gasifier
BFB	Bubbling Fluidized Bed gasifier
EF	Entrained Flow gasifier
TANESCO	Tanzania Electric Supply Company Limited
TFS	Tanzania Forest Agency
TNEP	National Energy Policy
CO	carbon monoxide
H_2	hydrogen
CO_2	carbon dioxide
CH_4	methane
H_2S	hydrogen sulfide
COS	carbonyl sulfide
N_2	gaseous nitrogen
NH_3	ammonia

HCN	cyanide
HCl	hydrogen chloride

CHAPTER ONE

INTRODUCTION

1.1 Background

Tea is undoubtedly the most popular beverage in the world (Reygaert, 2018;Debnath *et al.*, 2021;Vishnoi *et al.,* 2018), and due to its therapeutic benefits, including its anti-oxidative, anti-tumor, and anti-carcinogenic characteristics, it has gained more popularity recently (Taulo & Sebitosi, 2016). Both consumers and scientists have recognized and arouse interest in the numerous health benefits of tea as a result tea processing receives special attention because it has a direct impact on tea quality (Dias *et al.,* 2013;Saeed *et al.,* 2017).

The balanced flavor of made tea is achieved upon drying (Xia *et al.,* 2021;Teshome, 2019) because moisture is eliminated thus inhibiting fermentation and extending tea's storage life (Pou *et al.,* 2019).

Tea processing includes a number of energy-intensive unit activities, including plucking, withering, rolling, maceration, fermentation, drying, grading, and packing (Pou *et al.,* 2019) . Processing tea is a higher energy process that uses a ratio of 15:85 of electrical and thermal energy (Mwenda, 2016). While electrical energy powers motors, fans, humidifiers, and lighting, thermal energy is employed heavily in the withering and drying processes.

Itona tea factory is located at Itona Mufindi, in Iringa Tanzania to which both forest and tea plantations are found at large. As per Tanzania Forest Agency pine trees cover a big land as compared to other species of trees. Itona tea factories had to switch from oil furnaces to firewood-based boilers due to the rise in global oil prices and unstable, low – quality power supplied by TANESCO. According to Dutta & Baruah, 2014, the precise energy consumption of produced tea ranges from 4 to 10.4 kWh/kg. This transition is fraught with challenges, including the loss of forest cover and large quantities of money spent on buying firewood. The consequences of climate change have been amplified by the loss of trees, which has had an impact on tea production, resulting in lower yield (Muoki *et al*., 2020;Jayasinghe & Kumar, 2021).

In order to produce tea in a sustainable manner, it is vital to pay close attention to energy consumption trends in the tea industry (Gupta & Dey, 2010). As a result, a good use of the mixture of sawdust and tea waste could fulfill a portion of the energy necessary in tea processing.

Tea waste includes both factory processing waste and garden waste. The processing waste that is produced during the sorting or grading of made tea is disposed of with sewage waste, raising the acidity level of the soil (Harshana *et al.,* 2020). The extensive use of tea waste on soil results in a decrease in soil fertility. The fibers are removed from the primary tea during this process. Garden waste, on the other hand, is generated during the off-season when tea bushes are pruned (Kumar *et al.,* 2014).

During a 4-year pruning cycle, the amount of waste produced by tea shrub varies from 2 to 2.5 kg of wet matter per bush annually. As to Chowdhury *et al.,* 2016, the generation of tea waste accounts for around 2% of the entire tea production. Therefore, utilizing the tea waste in a productive way could provide some of the energy needed for the tea-processing process.

However, Large volumes of residues are produced during the processing of wood in Sao Hill Forest, and if they are not adequately managed, they can harm the surrounding ecology and beyond. These leftovers, which are primarily made up of wood shavings and sawdust, have significant energy potential but are not fully utilized in Tanzania.

In this work, an analysis is conducted to determine whether sawdust produced by sawmilling units in Tanzania, namely in Mufindi, can be used sustainably to produce syngas through a gasification process, making the units self-sufficient in terms of power demands.

In order to replenish some of the energy required in tea processing, gasification of a mixture of sawdust and tea trash found along Mufindi areas can replace the use of fossil fuels for energy generation. This ensures a sustainable source of energy while lowering the cost of drying tea for tea manufacturers. (Kumar, 2016).

However, Gasification of biomass is being considered by many major power companies in developed nations as a way to reduce greenhouse gas emissions (Lenz *et al.,* 2020). Relative to fossil fuels, the combination of sawdust and tea waste gasified for energy produces a lot less air pollution, less trash going to landfills, and less reliance on foreign oil.

1.2 Statement of the problem

An essential component of tea factories' functioning is their energy source. The tea company utilizes a lot of electricity from the power grid, off-grid diesel, and firewood, coal, or natural gas to meet its thermal energy needs. (Thirunavukkarasu and Sawle, 2022).

Enhancing the energy supply for tea manufacturers can be done in a few different ways. To enhance the energy-intensive tea producing process, for example, a Ugandan study suggested using systematic energy management and sustainable energy applications. (Efficiency and Solutions, 2019)

The most energy-intensive step in the tea-making process varies according on the kind of tea and how it is made. Nonetheless, research indicates that the energy-intensive phases of the tea-making process are the drying and withering phases. (Sharma *et al.,* 2019). Many strategies have been put forth to lower the energy consumption of these processes; one study suggested that installing newly designed furnaces, insulating the current furnaces and drying machines, and enhancing power supply systems could all contribute to lower energy consumption in the processing of tea. (salvatian *et al.,* 2018)

The industry and the area determine which energy sources are employed for the withering and drying processes. Nonetheless, firewood, solar energy, and geothermal energy are some of the most widely used energy sources. (Suyanto *et al.,* 2010). For example, tea leaves are dried using geothermal energy in Bali, Indonesia's Wayang Windu geothermal area. On the other hand, in some places, like Itona Tea Factory, incomplete firewood combustion is utilized as a source of energy for the withering and drying of tea leaves (Gunawan *et al.,* 2021).

Rising energy prices and unstable, poor power quality are two energy-related issues that Tanzania's tea industry is facing. The cost of energy is another important factor that impacts the total cost of making tea. The cost of production and the price of tea on the market have an impact on tea producers' profits. Sawdust and tea waste are available to the Itona Tea Factory as renewable energy sources; however, they must first be evaluated and measured in order to be matched with the factory's energy requirements.

1.3 Research objectives

1.3.1 Main objective

The main objective of this study is to determine the proportionate mixture of tea waste and sawdust which provides maximum energy output though gasification.

1.3.2 Specific objectives

i. To characterize tea waste and pine sawdust as fuel sources.
ii. To estimate the energy potential of tea waste and saw dust resources available for use at Itona tea factory.
iii. To determine the optimum ratio of the mixture between tea waste and sawdust for gasification applications.
iv. To analyze the energy requirements for Itona tea factory.

1.4 Research Questions

i. What are the properties of tea waste and saw dust as fuel sources for gasification?
ii. What is the Bio-energy potential of tea waste and sawdust resources available for use at Itona tea factory?
iii. What amount of the mixture will provide the optimum ratio of the mixture between tea waste and sawdust for gasification applications?
iv. What is the energy required by Itona tea factory for tea processing?

1.5 Significances of the study

The study will reduce the use of firewood by substituting it with syngas made from the gasification of the mixture of tea waste and saw dust.

The study also aims to reduce expenditure on firewood with savings shared among farmers and used to support community development.

By extracting the byproducts from their processing tea wastes, the tea industry can achieve zero waste management and improved profitability through cogeneration in a sustainable manner.

1.6 Justification

The conventional energy sources that are now available are costly, inconsistent, and occasionally of low quality. According to John (2017), the sustainability of Tanzania's energy-intensive tea production operations is negatively impacted by the imbalance of electric energy and the rising cost of imported fossil fuel. Globally, there is evidence that energy cost in energy intensive tea factories contributes about 25% to 40% of the total processing costs (Sebitosi *et al.,* 2016).

Additionally, the National Energy Policy, states that there are no standards for promoting the use of renewable energy sources in tea factories. By utilizing these resources, it is possible to improve the energy mix, reduce production costs, and eventually boost shareholder returns. The study offers the relevant details that policymakers in control of tea factories can utilize when creating corporate strategy plans, particularly with regard to energy management, conservation, and renewable energy exploitation.

LITERATURE REVIEW

2.1. Tea processing

Tea processing includes a number of energy-intensive unit activities, including plucking, withering, rolling, maceration, fermentation, drying, grading, and packing. Processing tea is a higher energy process that uses a ratio of 15:85 of electrical and thermal energy (Mwenda, 2016).

While electrical energy powers motors, fans, humidifiers, and lights, thermal energy is largely employed in the withering and drying processes. Mwenda *et al.,* (2015) state that producing tea in India requires 0.2 to 0.5 kWh/kg of electrical energy and 3.5 to 6 kWh/kg of thermal energy.

During tea processing at the Itona tea factory, heavy fuel oil and fuel wood provide the thermal energy needed, while standby generators and the national grid provide the electricity. Hence, renewable energy has potential role in sustainable energy supply for industries such as tea (Kumarihami & Song, 2020).

The EIA (2012) states that co-digestion of various feedstocks guarantees a stable process and can provide balanced biogas. According to a study done in Kenya, tea firms can reduce their energy costs by using organic waste (Njenga & Iiyama, 2017). Although this study did not measure the energy contained in bio-waste, it however shows that sawdust, briquettes, tea fluff, wet manure, and immature wood have respective caloric values of 25.03 kJ per g, 20.24 kJ per g, 21.67 kJ per g, 23.57 kJ per g, and 21.35 kJ per g. Gasification is the greatest process for optimizing the energy content extracted from biomass (Mckendry, 2002).

In addition, Ouwens, (2023) discovered that the gasification efficiency was more than 17% when compared to the production of electricity utilizing anaerobic digester gas. Gasification enabled a reduction in overall fuel wood use of more than 50% and a specific fuel wood utilization for drying tea of 0.4 kg fuel wood/kg of produced tea (Jayah, 2002).

2.1.1 Tea plucking

Plucking is the first step in the manufacturing process of tea and refers to the harvesting by hand of the tea plant (Piyathissa *et al.,* 2020). The plucking process occurs when the tea bush “flushes” or pushes out new leaf shoots.

For a fine black or green tea, the pluckers will take the first two leaves and one new bud. For oolong teas, the bud along with three or four leaves are plucked. For white tea, just the bud will be plucked (Kamunya & Ochanda, 2019).

Plucking is an extremely labor-intensive process (Shankarpure & Patil, 2023). To put it into perspective, it takes 5 kilograms of freshly harvested tea leaves to produce 1 kilogram of finished tea leaves. For white tea, since only the center bud is plucked, it takes 15 kilograms of freshly harvested tea leaves to produce 1 kilogram of finished tea leaves (Hasanuzzaman & Technologies, 2019). Generally, smaller and fewer tea leaves also produce a more expensive tea.

Plucking takes place in the growing season which varies from region to region and is weather dependent (Mallik, 2021). For example, plucking occurs between spring and autumn in Northern India and China. Whereas in Kenya, plucking can take place all year round since the weather is more constant (Muoki *et al.,* 2020).

The tea harvesting season in Tanzania varies depending on the region and altitude. According to Tea Epicure, the first harvest of the year, known as "Ichibancha," typically occurs from late March to early May. The second harvest, known as "Nibancha," takes place from June to the end of July, while the third harvest, known as "Sanbancha," takes place in August

Figure 2. 1: African woman plucking tea leaves on plantation (Piyathissa et al., 2020)

The quality of tea is influenced by various factors such as the altitude, climate, soil, and plucking standards (Owuor *et al.,* 2011). According to the International Specialty Tea Association, the first step in making a quality tea requires adherence to the plucking standard. The plucking standard that most people are familiar with is two leaves and a bud, the original plucking standard for quality green tea going back to at least the Tang dynasty. There are many other picking standards to suit the processing demands of different styles of tea

2.1.2 Tea Withering

The initial stage of tea processing is called "tea withering," which is the deliberate wilting of freshly picked tea leaves to lower their moisture content (Deb & Jolvis Pou, 2016). As soon as a tea leaf is removed from the plant, it starts to wilt or wither. (Prakash *et al.,* 2011).

The length of time that passes between when the leaves are picked in the field and when they arrive at their destination to be further processed, as well as the standard of care provided to them during this period, determine how much of this inevitable, uncontrollable withering the leaves endure. (Cowan-Gore & Sein, 2020).

In order to accomplish additional physical and chemical objectives and to limit the decline of moisture in tea leaves until it reaches a desirable level, tea manufacturers employ a balance of moisture and airflow during a controlled wither. (Anjum, n.d.).

Reducing the moisture level of the leaf makes it more flexible and malleable, which gets it ready for rolling and shaping. This is the physical purpose of withering. Withering's chemical purpose is to release grassy scents and enable flavor and aroma volatiles to form in the leaves. (Wu *et al.,* 2022).

Since many of the chemical components in tea break down into volatile compounds, the longer the wither, the more flavor and aroma chemicals emerge in the leaves.

The leaves start to use their stored carbohydrates for energy when they are cut off from their energy source (Teshome, 2019).

The breakdown of cell walls brought on by moisture loss triggers the activity of polyphenol oxidase and peroxidase, a process known as oxidation. At this point, chlorophylls also start to break down. Sustaining the withering process requires constant observation of temperature, humidity, and airflow(A. Sharma & Dutta, 2018).

Tea leaves can be carefully arranged on bamboo mats in the shade outside or inside in troughs with forced air to create a controlled wither. To expedite the procedure, the air could be heated. When the tea reaches the appropriate percentage of water loss, the withering process is finished (Deb & Jolvis Pou, 2016). To guarantee that the withering leaves wither uniformly, great attention is also paid to their density.

Furthermore, proper withering ensures that the leaves remain pliable enough to undergo subsequent processing steps without breaking or tearing apart (Aaqil *et al.,* 2023). However, if over-withered or under-withered, this can result in subpar quality tea due to loss of flavor or damage to the leaves' structure respectively.

Therefore, monitoring humidity levels and adjusting duration accordingly is critical for producing high-quality teas through this stage of processing.

Figure 2. 2: Withering process (Deb & Jolvis Pou, 2016)

2.1.2 Tea Rolling

Rolling is an important step in the tea processing process. The main purpose of rolling tea leaves is to damage the cell walls (Shao *et al.,* 2021). Rolling is where the leaves get squished and smashed to release their juices. This is done by twisting and pressing the leaves to extract the juices that are held inside (Kanwar, 2023).

This process helps to break down the cells in the leaves, which allows for the oxidation process to occur more quickly and evenly. Rolling can be done by hand or with machinery, depending on the size of the tea plantation and the desired level of quality (Shao *et al.,* 2021).

The texture of the tea leaves after rolling can vary depending on how much pressure was applied during this step. Some teas, like black tea, are rolled very tightly to create a small, twisted leaf shape. Other teas, like green tea, may only be lightly rolled or even left unrolled altogether (Pou *et al.,* 2019).

The machinery used for rolling can range from simple wooden rollers to complex machines that use a combination of heat and pressure to achieve a specific texture and flavor profile in the finished product (Pou *et al.,* 2019).

Figure 2. 3: Rolling tea leaves machine (Deb & Jolvis Pou, 2016)

2.1.3 Tea fermentation

Fermentation is a crucial step in tea processing that determines the final flavor profile of tea leaves (Wu *et al.,* 2022). The fermentation process is also known as oxidation. During this stage, enzymes present in the leaves interact with oxygen and other compounds to create new flavors and aromas. Oxidation levels play a significant role in the development of tea flavors.

Black teas are fully oxidized, giving them a robust and bold taste, while green teas are minimally oxidized, resulting in a light and refreshing flavor (Kilel, 2019). Factors affecting oxidation include temperature, humidity, and processing techniques such as twisting or bruising the leaves.

All these factors can influence how much oxygen reaches the enzymes within the leaf cells and therefore impact the final product's flavor profile. Understanding how to manipulate these variables is a critical aspect of producing high-quality artisanal tea with complex flavors that satisfy discerning palates worldwide.

Figure 2. 4: Fermentation process of tea (Kilel, 2019)

2.1.3 Tea drying

The crucial procedure of drying tea leaves improves their flavor and gives them shelf stability. The fermented leaves' moisture content drops from 50–70% to 2-3% throughout the drying process. The leaves become shelf-stable due to this decrease in moisture content, which also almost completely halts the oxidative activities inside the leaves (Chua *et al.,* 2019).

To create a pleasant tea, tea manufacturers regulate the air temperature, the amount of air passing over the tea, and the drying period (Kilel, 2019). When tea is dried too quickly, the outside of the leaves dries considerably faster than the inside, a process known as case hardening in the tea industry. When tea is dried too slowly, it stews.

Tea leaves can be dried in a number of ways, such as with commercial dryers, ovens, sunshades, charcoal fires, and heated floors. Two heat-related alternative processing techniques that might be considered separate processing steps or a component of drying for shelf-stability are finish-firing and roasting (Chan *et al.,* 2009).

Through the pyrolysis of the sugars and amino acids in the tea leaves, both techniques change the flavor. Finish-firing is the process of heating tea leaves for several hours at a very low temperature, either in an oven or in shallow bamboo baskets over hot coals (Chan *et al.,* 2009).

Contrarily, the process of roasting involves heating the tea to change its flavor and scent. Roasting typically imparts toasted, burnt overtones and results in a darker tea and infusion, depending on the length of time and temperature of the tea roasting process. (Chan *et al.,* 2009).

2.2 Biomass conversion technologies

Biomass is the term used to describe all materials that contain carbon in an organic form (Tursi, 2019). This organic form of carbon can be transformed into inorganic through photosynthesis by forming bonds with other elements such as hydrogen, and oxygen using solar energy.

The demolishing of these bonds (molecules) through physical or biological means, causes a closure in the cycle and making CO_2 to be regenerated. During the regeneration process, energy is released which can be converted into other forms of energy. Therefore, as long as this equilibrium is maintained between use and regeneration, biomass is a renewable or inexhaustible source of energy (Clauser *et al.,* 2021).

Biomass accumulates chemical energy in form of carbohydrates through combination of solar power and carbon dioxide during the process of photosynthesis. This has made it to be a potential energy source since the carbon dioxide captured during photosynthesis could be released when it burns (Jaiswal *et al.,* 2023). It is cheap and available in all forms such as forest and agricultural residues, wood, by-products of biological materials, organic components of municipal and sludge wastes, etc.

There are several ways to convert biomass into useful products which largely depends on biomass characteristics and the end product. The technologies applied in the conversion of biomass are mainly categorized under thermochemical or biological methods (Tursi, 2019).

Thermochemical conversion technologies involve the use of heat to convert biomass into energy (Chan *et al.,* 2019). These technologies include combustion, gasification, and pyrolysis. In combustion, biomass is burned to produce heat, which is then used to generate electricity. In gasification, biomass is heated in the presence of a limited amount of oxygen to produce a gas that can be used as fuel. In pyrolysis, biomass is heated in the absence of oxygen to produce a liquid that can be used as fuel (Pang, 2019).

Biochemical conversion technologies involve the use of microorganisms or enzymes to convert biomass into energy (Lee *et al.,* 2019). These technologies include anaerobic digestion, fermentation, and enzymatic hydrolysis. In anaerobic digestion, microorganisms break down biomass in the absence of oxygen to produce biogas. In fermentation, microorganisms convert biomass into ethanol or other chemicals. In enzymatic hydrolysis, enzymes are used to break down biomass into sugars, which can then be converted into biofuels (Hossain, 2019).

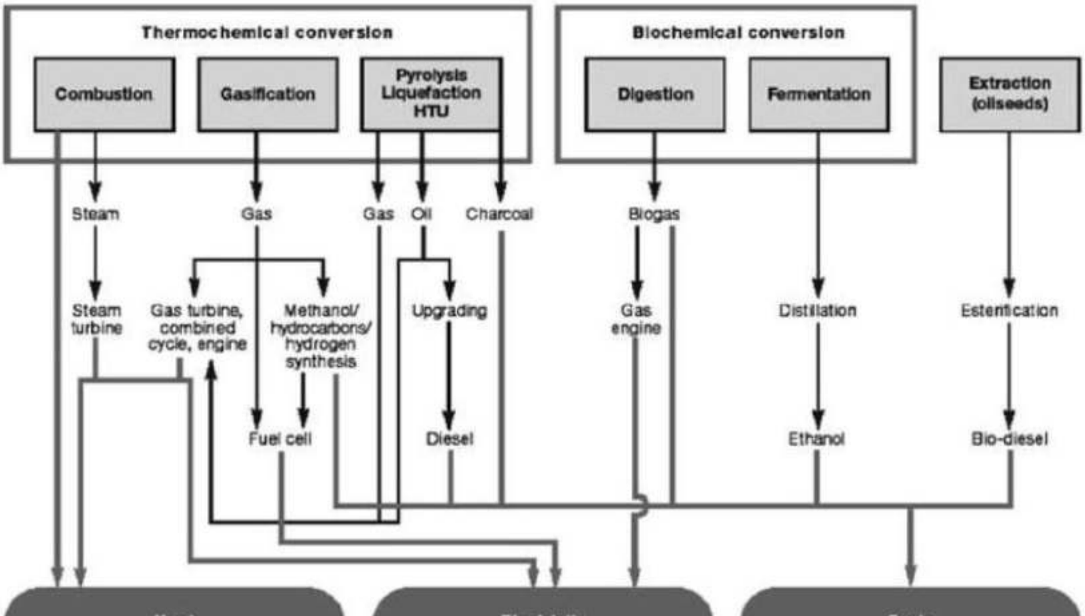

Figure 2. 5: Biomass conversion processes (Pang, 2019)

2.3 Theory of gasification

According to Mazaheri et al., (2019), gasification is one of the most effective processes for turning carbon-based fuel into energy. The design and operation of a gasifier utilized for the production of bioenergy involve an understanding of the gasification process, gasifier configuration, gasifier size, feedstock characteristics, and the operational parameters of the gasifier.

Through the process of gasification, the carbonaceous feedstock is changed into a chemical or gaseous fuel that can be burned once again to release energy or used to create valuable molecules like hydrogen (Muh *et al.,* 2019).

Gasification and combustion are comparable processes, but they differ in the way the resulting gas is handled and the amount of energy contained in its chemical bonds (Chhiti & Kemiha, 2013). The energy released during burning is different because those chemical links are broken. (Mazaheri *et al.,* 2019).

The main goal of gasification is to create gases with a high hydrogen-to-carbon ratio by taking carbon out of the hydrocarbon fuel and replacing it with hydrogen. (Mazaheri *et al.,* 2019).

2.3 Gasification

Any carbonaceous raw material, such as biomass, can be gasified technologically to create fuel gas, or syngas, as it is also called. (AlNouss *et al.,* 2018). Gasification occurs in a gasifier, which is usually a high temperature/pressure vessel where oxygen, air, and steam come into direct contact with the feed material, according to AlNouss *et al.,* (2020). This sets off a series of chemical reactions in the feed that result in the production of syngas and ash/slag.

Syngas is primarily composed of the colorless, odorless, and highly flammable gases carbon monoxide and hydrogen (H_2) and is utilized for a variety of applications. In a water-gas-shift reactor, the syngas can be further altered (or shifted) to only hydrogen and carbon dioxide by adding steam and reacting over a catalyst. (Sarafraz *et al.,* 2019).

Burning hydrogen produces only heat and water, which means that there is no carbon dioxide released in the exhaust when electricity is produced (Zohuri & Future, 2019). What's more, diesel and gasoline can be produced from hydrogen-enriched syngas.

Gasification technologies offer a unique way to create polygeneration plants that generate several products (Parraga *et al.,* 2018). Effortlessly extracting carbon dioxide from syngas can save it from being released into the atmosphere and allow it to be used for safe storage or improved oil recovery (Shreyash *et al.,* 2021).

2.3.1. Gasification Fundamentals

A partial oxidation process is called gasification (Barbuzza *et al.,* 2019). Partial oxidation is a relative word that merely indicates that less oxygen is consumed during gasification than would be needed for the same amount of fuel to burn or undergo complete oxidation. Only 25 to 40 percent of the potential oxidant pure oxygen or air is usually needed during gasification in order to produce enough heat to gasify the fuel that is still unoxidized and produce syngas (Xu *et al.,* 2018).

The primary combustible byproducts of gasification are hydrogen and carbon monoxide because only a tiny amount of the carbon is completely oxidized to form carbon dioxide and water. The heat produced during partial oxidation provides most of the energy needed to break the chemical bonds in the feedstock, drive the other endothermic gasification events, and raise the temperature of the gasification products' end product (Y. Zhang *et al.,* 2019).

2.3.2. Gasification Process

Processes including pyrolysis, drying, oxidation, and reduction are frequently used in the gasification of biomass. The moisture content of the biomass lowers during the drying cycle (Valderrama Rios *et al.,* 2018). It occurs between 100 and 200 degrees Celsius and reduces the moisture content of the biomass by up to 5%.

The moisture percentage of raw biomass varies greatly, from 5% to 35%. During the pyrolysis stage, biomass undergoes thermal decomposition without oxygen or air, releasing volatile compounds in the process. The biomass is thus converted into solid charcoal, and gasses like carbon monoxide, hydrogen, carbon dioxide, and hydrocarbon gases are emitted as a result (Wazeer & Dubey, 2018).

2.3.3. Chemistry of Gasification

The chemical processes during gasification can proceed in a variety of ways, depending on the feedstock used, the temperature, pressure, and other gasification variables. (Safarian *et al.,* 2019).

Combustion processes are involved in the gasification process. Instead of using a stoichiometric excess of oxidant, as is the case with classical combustion, it usually uses one-fifth to one-third of the theoretical oxidant (Park *et al.,* 2022). Gasification is a partial oxidation process that mostly produces hydrogen and carbon monoxide as flammable byproducts, with just a small amount of the carbon being fully oxidized to carbon dioxide.

The majority of the energy needed to power the endothermic gasification reactions is provided by the heat generated by the partial oxidation (Broer & Peterson, n.d.). The primary chemical processes that occur during a gasification process involve carbon, CO, CO_2, H_2, water (steam) and methane, as follows

The combustion reactions:

1. $C + ½ O_2 \rightarrow CO$ (-111 MJ/kmol)

2. $CO + ½ O_2 \rightarrow CO_2$ (-283 MJ/kmol)

3. $H2 + ½ O_2 \rightarrow H_2O$ (-242 MJ/kmol)

Other important gasification reactions include:

4. $C + H_2O \leftrightarrow CO + H_2$ Water-Gas Reaction (+131 MJ/kmol)

5. $C + CO_2 \leftrightarrow 2CO$ Boudouard Reaction (+172 MJ/kmol)

6. $C + 2H_2 \leftrightarrow CH_4$ Methanation Reaction (-75 MJ/kmol)

With the aforementioned, at typical gasification working circumstances, the combustion reactions are essentially completed. Additionally, the three heterogeneous reactions (reactions 4 to 6) can be reduced to two homogeneous gas phase reactions (reactions 7 and 8 below) that are steam methane-reforming and water-gas-shifting, respectively, under the condition of high carbon conversion. These reactions collectively are important in determining the composition of the final equilibrium synthesis gas.

7. $CO + H_2O \leftrightarrow CO_2 + H_2$ Water-Gas-Shift Reaction (-41 MJ/kmol)

8. $CH_4 + H_2O \leftrightarrow CO_2 + 3H_2$ Steam-Methane-Reforming Reaction (+206 MJ/kmol)

In the low-oxygen, reducing environment of the gasifier, most of the feedstock's sulfur coverts to hydrogen sulfide, with a small amount forming carbonyl sulfide (Gururani *et al.,* 2022).

Chemically bound nitrogen in the feed often transforms into gaseous nitrogen, ammonia, and hydrogen cyanide in trace amounts. Hydrogen chloride is the first product of chlorine conversion. Generally speaking, the fuel's amounts of sulfur, nitrogen, and chloride are so low that they barely affect the primary syngas components of H_2 and CO.

The different ash and slag fractions as well as gaseous emissions contain trace elements related to both organic and inorganic feed components, such as mercury, arsenic, and other heavy metals. These elements must be removed from the syngas before it is used again. (Orjales *et al.,* 2018).

2.3 Gasifiers

Gasifiers are devices that convert carbonaceous materials such as biomass, coal, or petroleum into gases, including nitrogen (N_2), carbon monoxide (CO), hydrogen (H_2), and carbon dioxide (CO_2) (Janajreh *et al.,* 2021). The process is achieved by reacting the feedstock material at high temperatures (typically >700 °C) in an oxygen-starved environment, without combustion, via controlling the amount of oxygen and/or steam present in the reaction (Gomaa *et al.,* 2020).

The size and kind of gasifier depend on several parameters, including the need of the products, moisture content, and fuel availability. This type of gasifiers includes:

2.3.1 Downdraft Fixed Bed Gasifier (DDFB)

In this type of gasifier, the feedstock and gasifying agent are both introduced from the top of the gasifier and move downward (P. Sharma *et al.,* 2020). The downdraft gasifier is known for its high syngas yield, which occurs because the downward movement of feedstock and gasifying agent allows the feedstock to break down effectively in the presence of large amounts of heat (Rahman *et al.,* 2019). Since the feedstock is continually subjected to high-temperature conditions, syngas produced in downdraft gasifier is usually of high purity, containing low amounts of tar (Loha *et al., 2018).*

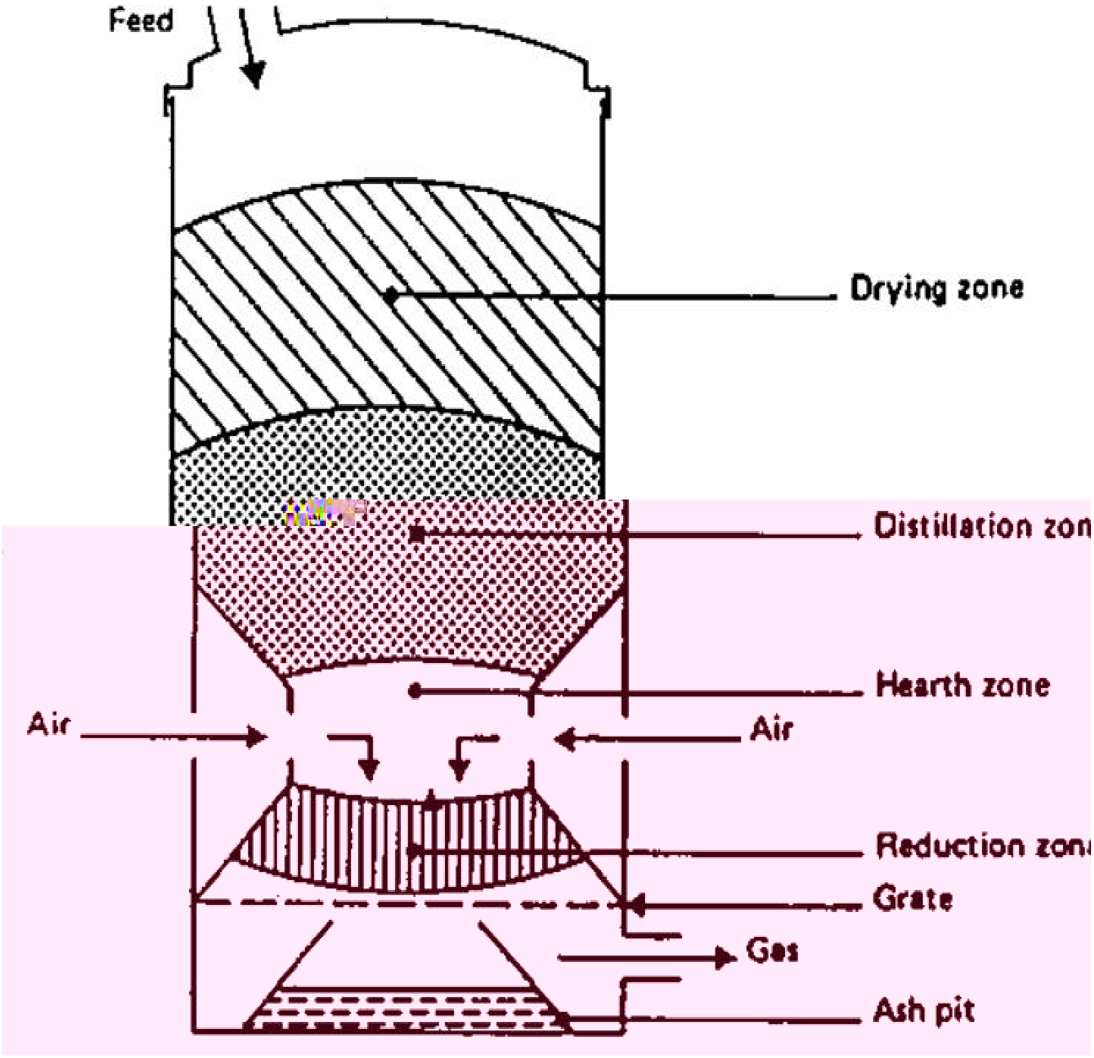

Figure 2. 6: Downdraft Fixed Bed Gasifier (Zhang et al., 2019)

2.3.2 Updraft Fixed Bed Gasifier (UDFB)

In this type of gasifier, the feedstock or 'fuel' is introduced from the top of the gasifier, while the gasifying agent is introduced from the bottom (Corredor *et al.,* 2022). The feedstock moves downward, while the gasifying agent ascends upward (Abubakar *et al.,* 2019). This arrangement ensures that the feedstock comes in close contact with the gasifying agent, which supplies heat energy for thermal conversion.

The updraft gasifier is known for its ease of operation as well as energy efficiency and feedstock-conversion efficiency (Devi *et al.,* 2020).

The only difference between this gasifier and the downdraft type is the direction of the air, oxygen, or steam flowing through the bed (Xiang *et al.,* 2020). Although this method's throughput isn't very high, its thermal efficiency is comparable to that of down-draft systems. Methanation for the generation of synthetic natural gas is facilitated by the substantial volume percentage of methane in the produced gas. At normal operating temperatures, tar generation is likewise substantial, meaning higher cleaning expenses. (Loha *et al.,* 2018).

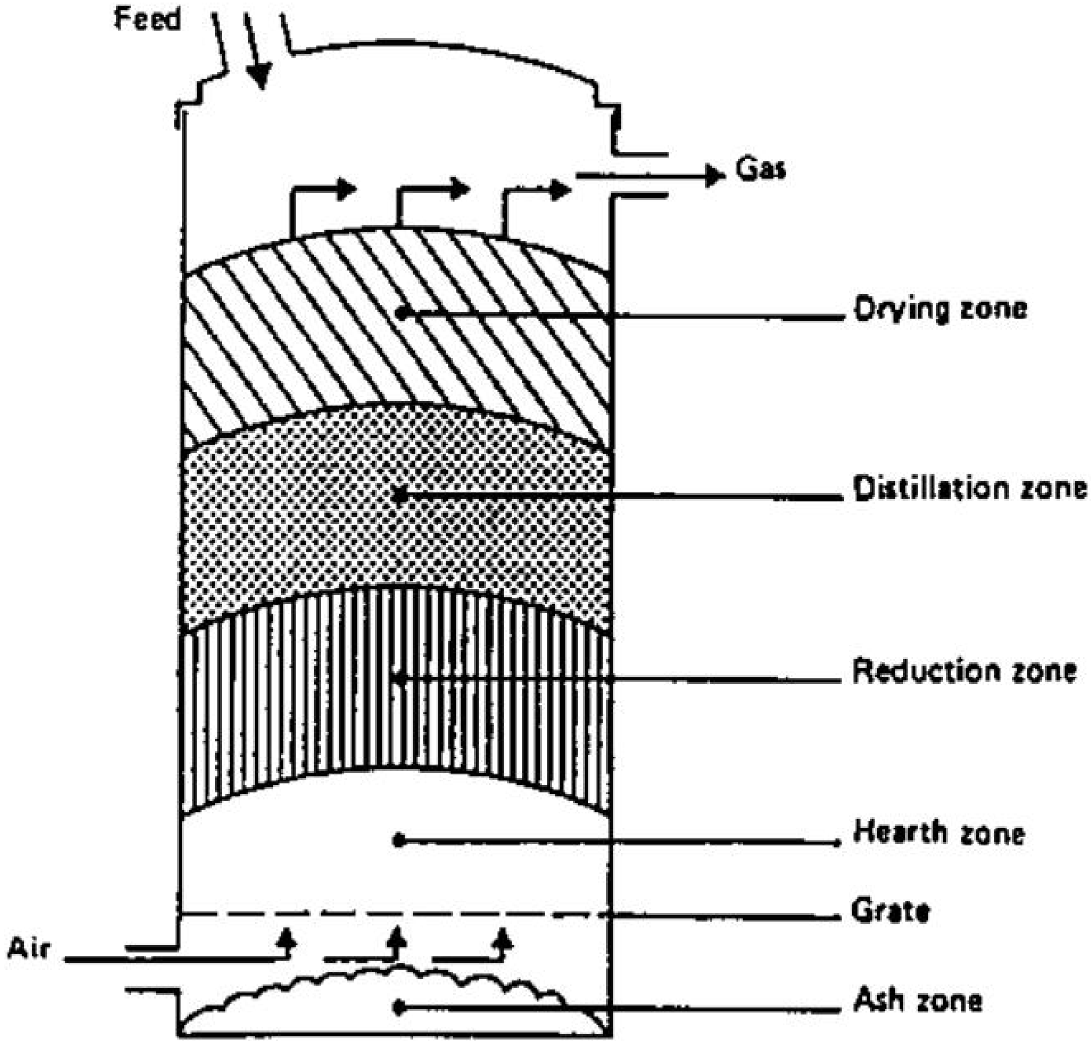

Figure 2. 7:Updraft Fixed Bed Gasifier (Zhang et al., 2019)

2.3.3 Fluidized bed gasifier

A fluidized bed may be circulating or bubbling. For the burning of coal, biomass, and waste in medium to large heat and power facilities (>5 MW), fluidized beds are fairly frequent used. The oxidizing agent fluidizes the fuel in the fluidized bed (Merrett & Whitty, 2019). The fuel must be reactive because the operational temperature is lower. In general, fluidized beds call for proper feedstock preparation, taking moisture content and solid fuel particle size into account. (Loha *et al.,* 2018).

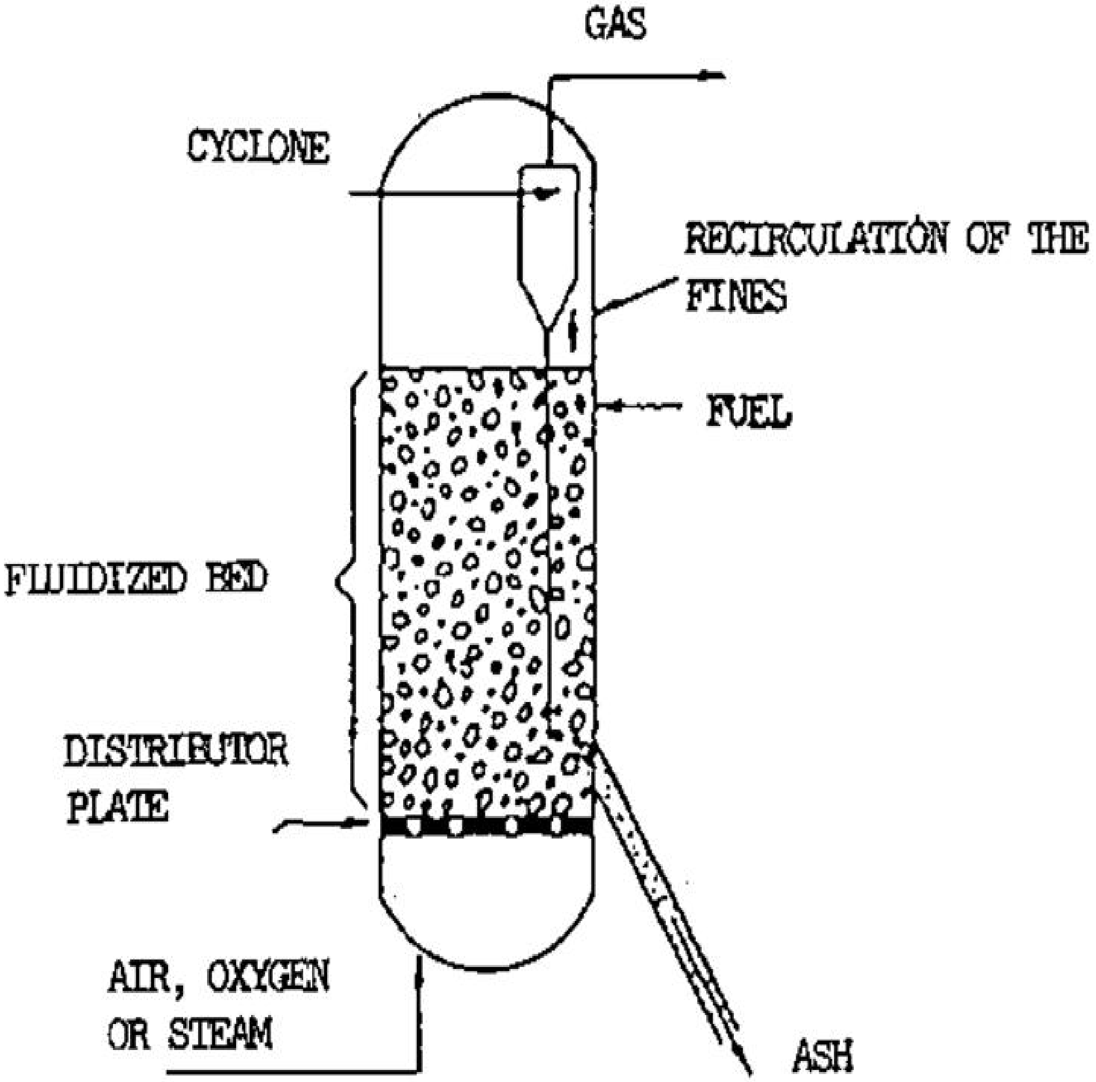

Figure 2. 8: Fluidized bed gasifier (Zhang et al., 2019)

2.3.4 Entrained flow gasifier (EF)

This technology uses oxygen to gasify the fuel, either liquid or solid, that is fed to the entrained flow gasifier. Reaction occurs at high temperatures and frequently high pressures in a dense aerosol cloud. Although a high throughput is possible, the thermal efficiency is decreased since the high-temperature syngas must be extensively cooled before cleaning. (Loha *et al.,* 2018). The EF-gasifier has low methane and tar production but high oxygen requirements, making it well-suited for producing H_2-rich gas. For highly large (>1,000 MW thermal) bio-refinery systems, EF-gasifiers are the only viable alternative

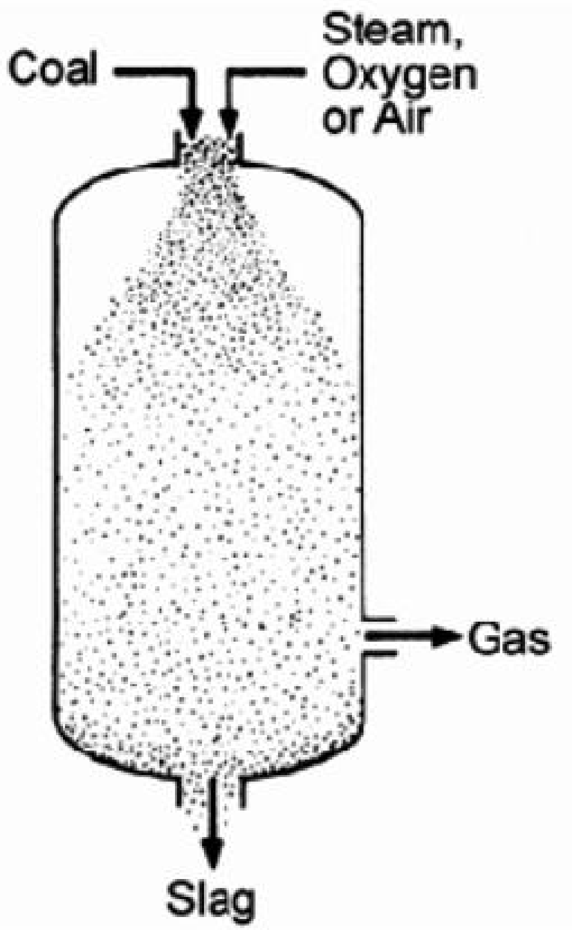

Figure 2. 9: Entrained flow gasifier (Zhang et al., 2019)

2.4 Benefits of gasification technology

Gasification is an appealing alternative for a range of applications due to its many advantages. Organic compounds undergo gasification, which produces carbon dioxide, hydrogen gas, and carbon monoxide. Because less air is used in the process, contaminants such nitrogen oxides are less likely to occur and the energy recovery efficiency is increased.

When compared to other technologies like incineration, gasification of agricultural wastes offers numerous environmental benefits. For these reasons, gasification offers both environmental and financial advantages. It can be used to transform inexpensive feedstock, such as sawdust and tea waste, into useful goods, such as electricity, fertilizers, and fuels.

Additional applications of the gasification process include the production of methanol and compounds like urea and ammonia, which are used as the building blocks of numerous fertilizers. Gasification of waste results in a reduction of methane emissions, a decrease in landfill site requirement, and a decrease in fossil fuel use. Waste gasification is therefore utilized to improve recycling systems.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Characterization of Tea waste and Sawdust

The biomasses used in this study were saw dust and tea waste gathered from Sao hill forest and Itona Tea Factory/Plantations respectively located in Tanzania's Mafinga district in Iringa region. Since the immediate testing was not possible, the samples were transferred into a clean, sealable air –tight container or bag ensuring the moisture is preserved until the sample is tested.

Moreover, for moisture content determination the packed samples were weighed immediately after sampling to prevent the moisture from accidentally getting out of the package walls.

The feedstocks were then milled into a fine powder with an average particle size of 200 µm after being dried for a week in atmospheric conditions.

3.1.1 Proximate and Ultimate Analyses

According to the ASTM E 870-82 technique, proximate analysis was done on each biomass using a TGA-701 thermogravimetric analyzer to quantify the amount of moisture, ash, volatile matter, and fixed carbon in the investigated samples. As a result, a series of ceramic crucibles were weighed before being filled with a maximum of 5.0 g of powdered biomass sample. The temperature was raised to 900°C under nitrogen atmosphere after the crucibles when placed inside the instrument and the cover was closed.

The scope of ultimate analysis is to figure out how much carbon, hydrogen, and nitrogen are in the biomass. According to the ASTM D5373 analysis procedure, the investigations were conducted with a TrueSpec CHN elemental analyzer, and the outcomes were given as dry basis of biomass. Up to 0.05–0.1 g of sample was placed into a tin capsule that had already been accurately weighed before being loaded into the CHN analyzer to do the analysis. The data were gathered by the TrueSpec LECO program while the furnace was heated to 950 C with a continuous supply of helium and oxygen.

3.1.2 Computation of high heating value

The elemental composition was used to compute the higher heat value (HHV) using the following energy balances. (Zhang *et al.,* 2010) Equation 3.1

$$HHV = \frac{35.5x\%C+142.3x\%H-15.4x\%O-14.5x\%N}{100} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 3.1$$

Where C, H, O, N are respectively carbon, hydrogen, oxygen and nitrogen composition percentages. Using the following formulas, the oxygen value is indirectly determined while assuming there is little sulfur present. (Zhang *et al.,* 2010) Equation 3.2.

$$O\% = 100\% - ash\% - C\% - H\% - N\% \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.2$$

3.1.3. Determination of the moisture content

The samples were broken up into smaller bits and kept in a muffle furnace set at 105 °C for a whole day. Equation 3.3 was used to determine the moisture content of garden waste leaves and branches as well as manufacturing tea waste.

$$MC = \frac{W_{ws} - W_{ds}}{W_w} x100 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

3.3

W_{ws} = Weight of wet sample

W_{ds} = Weight of dry sample

3.1.4. Determination of calorific value

A bomb calorimeter was used to measure the calorific value of the sample. A bomb-calorimeter measures the amount of heat produced when a sample is burned under controlled conditions in a closed vessel that is submerged in water and has an oxygen atmosphere.

A calorimeter is used to measure the temperature increase in the surrounding water as a result of the heat created while burning, which is determined by the combustion process. Equation 3.4 provides the calculation used to compute the sample's calorific value.

$$Calorific\ Value\ \left(\frac{kWh}{kg}\right) = \frac{W_w\ x\ (T_2 - T_1)}{W_s}\ x\ C \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 3.4$$

where,

W_w = Weight of water equivalent to calorimeter (g)

T_1 = Stabilized temperature before firing (°C)

T_1 = Maximum temperature after firing (°C)

W_s = Weight of sample (g)

C = 0.00116 (Constant)

3.2. Estimation of Energy Potential of Tea Waste and Sawdust

Energy balances was applied to calculate energy potentials of tea waste from two sources namely factory and garden source.

3.2.1. Factory Tea Waste

Equation 3.5 was used to calculate the factory tea waste's energy potential.

$$E_p(kWh) = P(Kg)x0.02F_{cv}(kWh/kg) \quad \text{……………………………………….3.5}$$

where,

E_p = Total energy (kWh)

P = Tea production (kg)

F_{cv} = Calorific value of tea waste from the factory (kWh/kg)

0.02 = Constant, percentage of tea waste generated

3.2.2 Garden Tea Waste

The energy potential of tea bush waste was calculated by using Equation 3.6

$$E_p(kWh) = B_w(Kg)xNxA(h_a)G_{cv}(kWh/kg) \quad \text{………………………………..3.6}$$

where,

E_p = Total energy (kWh)

B_w = Waste from tea bush (kg)

N = Total number of tea bush/hectare

A = Plantation area of the tea bush (ha)

G_{cv} = calorific value of the waste's tea bush (kWh/kg)

3.2.3. Energy Potential of Saw dust

Sawdust is the microscopic fragments of wood that fall from a saw as powder. Put another way, sawdust is essentially a waste product of small particles that are available in large quantities in the southern region of Tanzania as heaps from sawmills, pulp and paper mills, and wood processing industries. Most of these industries burn off sawdust, which pollutes the environment.

Through the use of a precision balance and a sieve set with mesh wire cloth ranging in size from 0.08 to 6.30 mm, the particle size of sawdust was ascertained through sieve analyses. In order to ascertain the sample's bulk density, the sawdust sample was placed in a container with known mass and volume and shaken periodically to guarantee that any remaining air spaces were completely eliminated. The mass to volume ratio of the sample served as the definition of the bulk density Equation 3.7

$$Bulky\ density = \frac{m - mo}{v} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.7$$

where: m is the mass of the sample and container, mo the mass of the container and V is the volume of the container.

It was expected that the sawdust would be pyrolyzed for energy generation in order to determine the quantity of energy that can be generated from wood waste. Thus, the amount of syngas that may be produced from sawdust served as the basis for the computations. The quantity of energy contained in a certain unit of a biomass sample is known as its energy content, and it is typically expressed as the heat of combustion. For measuring energy content, heating value (HV) or calorific value

(CV) is typically utilized. Higher heating value (HHV) and lower heating value (LHV) are the two types of heating values that are commonly employed.

The HHV (in MJ/kg) of biomass on a dry basis was estimated from the results of the ultimate analysis (Asibor *et al.,* 2019) and ash content from proximate analysis according to Equation 3.8 (Asibor *et al.,* 2019;Cai *et al.,* 2017)

$$HHV_{DB} = 0.3491EC_{C,DB} + 1.1783EC_{H,DB} + 0.1005EC_{S,DB} - 0.015EC_{N,DB} - 0.1034EC_{O,DB} - 0.0211A_{DB} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

3.8

ADB stands for the ash content on a dry basis, and EC stands for elemental composition. C, H, S, N, and O stand for carbon, hydrogen, sulfur, nitrogen, and oxygen, respectively. According to Waldheim and Nilsson (2001), the combustible gas components of syngas are H2, CO, and CH4, with standard HHVs of 12.76 MJ/m3, 12.63 MJ/m3, and 39.76 MJ/m3, respectively. Using these figures, the wood gas's energy content was calculated using Equation 3.9

LHV_{syngas} (MJ/m^3) = 12.76 × %H + 12.63 × %CO + 39.76 × %CH_4 ……………..…3.9

where the percentage compositions of hydrogen, carbon monoxide, and methane in the syngas are denoted by the symbols %H, %CO, and %CH4. The average thermal efficiency of the gasification process or wood gasifiers was calculated using Equation 3.10 (Rajvanshi, 1986)

$$\varepsilon_{gas} = \frac{\Delta H_{gas}\left(\frac{MJ}{m^3}\right) x V_{gas}(m^3)}{\Delta H_{wood}\left(\frac{MJ}{kg}\right) x 1(kg)} x 100\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.10$$

where ΔH_{gas} is the calorific value of the syngas produced from one kilogram of wood, ΔH_{wood} is the net calorific value per kilogram of wood and V_{gas} is the volume of gas obtained from one kilogram of wood.

Knowing ε_{gas} the amount of syngas obtainable from wood waste generated per day at our case study site was estimated using Equation 3.11

$$V(m^3/day) = \varepsilon_{gas} x m x V_{gas} \quad \ldots\ldots 3.11$$

where V is the daily volume of gas in milliliters (m^3), m is the amount of sawdust produced, and ε_{gas} is the ratio of syngas to biomass. Equation 3.12 was used to calculate the energy potential of the wood gas based on the volume determined by Eq. 3.11 and the syngas's calorific value.

$$EP(MJ/day) = V x LHV_{syngas} \quad \ldots\ldots 3.12$$

where EP represents the energy potential. The daily electric power conversion potential P_{ep} of the obtainable syngas was estimated using Eq. 13.

$$P_{ep} = LHV_{gas}\left(\frac{MJ}{m^3}\right) x V(m^3) x \varepsilon_{gas} x \frac{1kWh}{3.6(MJ)} \quad \ldots\ldots 3.13$$

Assuming a value for the electric efficiency of a gas engine as provided in (Nzali et al., 2019), the achievable power output was obtained following Eq. 14:

$$P_{el} = \varepsilon_{electric} x(1 - \%loss) \quad \ldots\ldots 3.14$$

where P_{el} represents the daily electric power, $\varepsilon_{electric}$ is the electric efficiency of the system. The energy potential for the various subdivisions in Mufindi per week was finally estimated using the estimates of the wood waste quantities generated in each of the five subdivisions along with the estimated HHV of the sawdust. This was done using Equation 3.15

$$EP_x = MxHHV_{DB} \ldots\ldots 3.15$$

where EP_x represents the energy potential per Subdivision x and M (tons/week) is the amount of sawdust produced per Subdivision.

3.3. Optimum Ratio of The Mixture Between Tea Waste and Saw Dust.

The ideal ratio of tea waste to sawdust for gasification is determined by a number of variables, including the feedstock's composition, the desired syngas composition, and the parameters of the gasification process.

In this study, the ideal ratio of sawdust to tea waste was ascertained through experimentation with various ratios of tea waste to sawdust, followed by an analysis of the calorific value and syngas composition. The ideal ratio was defined as one that yields the appropriate calorific value or syngas composition with the maximum yield and quality.

3.4. Energy Requirements for Itona Tea Factory.

An energy audit was performed to determine the Itona tea factory's energy requirements. This made it easier to pinpoint the locations of energy consumption and potential energy-saving opportunities.

According to Mwenda *et al.,* 2015, tea production and processing is energy-intensive. To produce one kilogram of tea, approximately 3-6 kWh of thermal energy is required, mainly supplied from wood combustion, and 0.2-0.5 kWh of electrical energy from the grid and diesel generators.

CHAPTER FOUR

RESULTS AND DISCUSSION

This section outlines the results and provides a brief explanation of their significance within the study's framework.

4.1. Characterization of Tea Waste and Sawdust

Tables 4.1 and 4.2 provide the condensed findings of the calorific value, proximate analyses, and final analyses of sawdust and tea waste.

Table 4. 1: Proximate and ultimate analysis of pine sawdust

sample	Proximate analysis (%)				Ultimate analysis (% dry basis)				
	NCV (MJ/Kg)	Moisture content	Volatile Matter (dry)	Fixed Carbon (dry)	Ash (dry)	C	H	N	O
S1	19.011	9.99	72.56	14.98	0.27	49.96			
S2	18.675	10.95	73.14	14.32	0.35	53.68			
S3	18.924	10.65	72.82	14.92	0.31	50.86			
Average	18.87	10.53	72.84	14.74	0.31	51.50	6.1	0.56	40.84

Table 4. 2: Proximate and ultimate analysis factory tea waste

sample	Proximate analysis (%)				Ultimate analysis (% dry basis)				
	NCV (MJ/Kg)	Moisture content	Volatile Matter (dry)	Fixed Carbon (dry)	Ash (dry)	C	H	N	O
T1	18.312	41.25	63.57	18.76	4.98	48.82			
T2	17.875	43.92	64.73	18.42	4.38	52.68			
T3	18.413	42.75	64.06	18.65	0.50	50.66			
Average	18.20	42.64	64.12	18.61	4.62	50.72	5.61	0.46	41.22

4.1.1. Calorific Value

Figure 4.1 shows a comparative graph of caloric value for saw dust and tea waste from the calorimetry experiment.

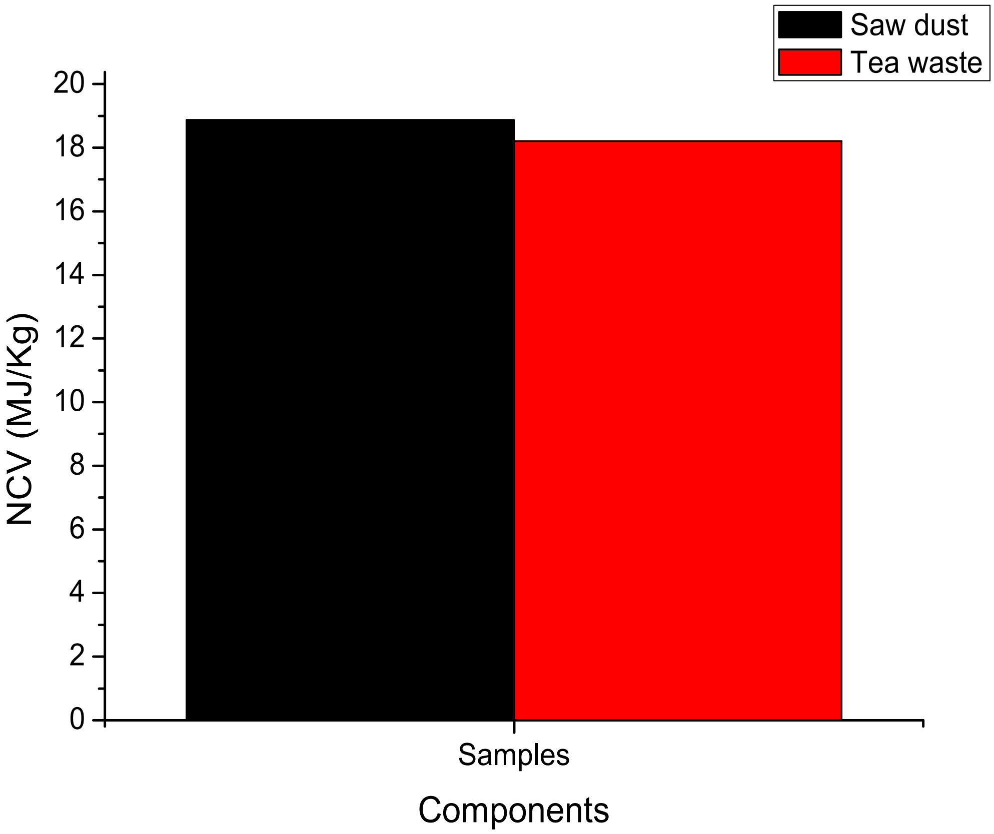

Figure 4. 1: Comparison of calorific value of saw dust and tea waste

As can be seen in Figure 4.1, sawdust has a larger calorific value than tea trash. For sawdust and tea trash, the NCVs are 18.87 MJ/kg and 18.2 MJ/kg, respectively. The fuel has more heat when its calorific value is higher. This suggests that sawdust has a greater potential for generating electricity than tea waste.

Additionally, a rise in gasification's heating value results in a reduction in gasification's H_2 concentration while increasing carbon conversion, cold gas efficiency, and CO concentration (Liu & Kojima, 2004).

4.1.2. Proximate Composition

Comparison of proximate components of the wood pellet and wood chip is shown in Figure 4.2

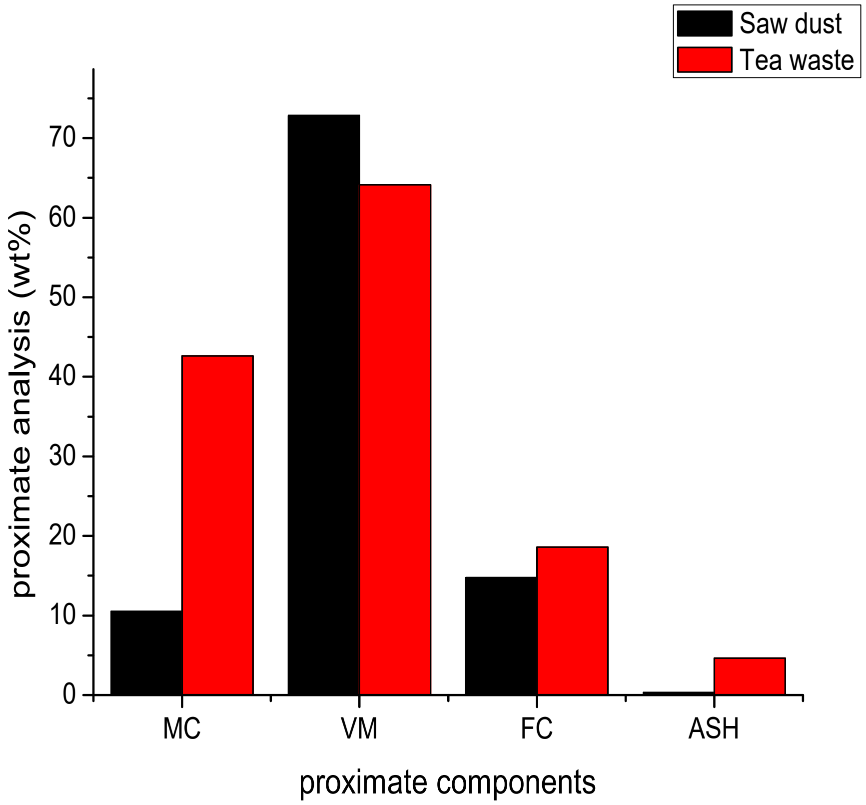

Figure 4. 2: Comparison of proximate composition in sawdust and factory tea waste

The moisture level of the tea waste is marginally higher than that of sawdust, as shown in Figure 4.2. For sawdust, the moisture level is 10.52%, whereas for tea trash, it is 42.64%. Moisture has an impact on the fuel's energy value.

The fuel's energy worth decreases as the moisture content rises. Furthermore, a high moisture content in biomass feedstock is undesirable because it lowers the temperature during the oxidation process, which prevents the hydrocarbon inside a gasifier from fully breaking. (Sharma *et al.,* 2011).

Additionally, Figure 4.2 shows that sawdust has mass losses of 72.84% and 64.12%, respectively, making it more volatile than tea trash. Higher carbon conversion, cold gas efficiency, and syngas (CO and H2) concentration are implied by feedstock with a high volatile component (Liu & Kojima, 2004).

Interestingly, the fixed carbon content of the tea trash is 18.61% higher than that of the sawdust, which is 14.74%. The carbon in the burned residue left over after volatile matter has been removed is known as fixed carbon in biomass. The rate at which fixed carbon transforms into gases can be used to calculate the rate of gasification and the resulting product.

In terms of ash content, tea waste is defined as an ash-rich sample that contains more than ten times the amount of ash found in sawdust. In sawdust, the average ash percentage is 0.31%, but in tea trash, it is 4.62%. The bark to sawdust ratio is greater in the tea trash. There is more ash since the bark has a high mineral concentration. It's possible that some of the ash was contaminated with biomass, such as dirt, dust, soil, or any other kind of impurity (Basu, 2010).

Ash content lowers a gasification process's carbon conversion, lowers the calorific value of fuel, and creates undesirable deposits inside reactor components (Liu & Kojima, 2004).

Alkali metals, particularly silica, are known to be present in the ash and can lead to agglomeration, fouling, and corrosion in gasification components (Mettanant *et al.,* 2009). But because they can act as a catalyst for the carbon gas reaction, these alkali metals contained in ash can also be advantageous to the gasification process (Raveendran *et al.,* 1996).

4.1.3. Ultimate (elemental) Composition

Figure 4.2 displays the computed elemental analysis findings for the chosen biomass sample.

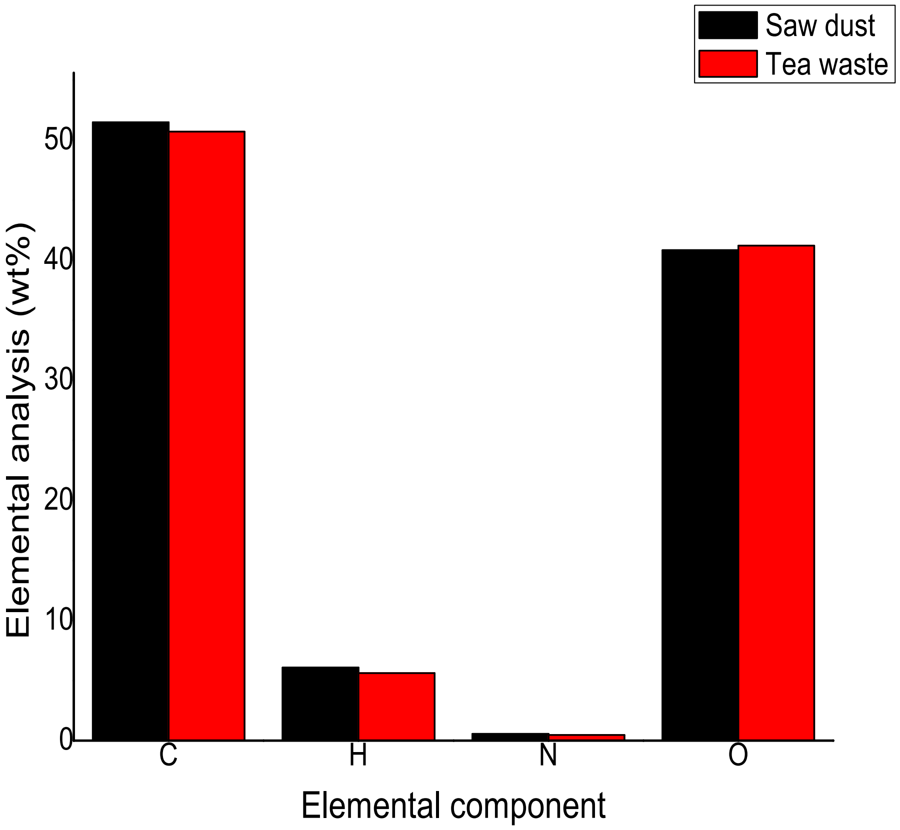

Figure 4. 3: Comparison of elemental components of sawdust vs tea waste

To ascertain the chemical balance and calorific value of biomass, these constituents must be analyzed. It is evident from the data that the main elements in the biomass samples are carbon and oxygen.

Compared to tea waste, sawdust has a higher carbon concentration. For sawdust and tea trash, the average carbon concentration is 51.50% and 50.72%, respectively. Because the carbon in the ultimate analysis includes the carbon in the volatile matter, it should be noted that the carbon content in the ultimate analysis is greater than the fixed carbon in the proximate analysis. Char product refers to the carbon that remains after devolatilization (Basu, 2010). increased carbon matter results in increased reactivity and, hence, higher NCV. This helps to explain why sawdust has a higher NCV than tea trash. Calculating carbon content also aids in determining CO_2 emissions. (Caillat and Vakkilainen, 2013).

While the sawdust has a slightly greater hydrogen content than tea trash, the tea waste has a slightly higher oxygen content than sawdust. In contrast to tea trash, which has a hydrogen and oxygen concentration of 40.84% and 41.22%, respectively, saw dust has a hydrogen level of 6.1% and an oxygen value of 5.61%. According to Basu (2010), the hydrogen and oxygen in elemental analysis only pertain to the organic portion of the biomass sample and do not contribute to the moisture content that was obtained through proximate analysis.

The calculation of the net calorific value depends on the hydrogen content. The conversion of solid biomass into liquid fuel is hampered by the high volatile yield caused by the high oxygen content in biomass (Basu, 2010).

In both samples, the nitrogen content was less than 1%. The low nitrogen level in the two biomass samples—0.56% in sawdust and 0.46% in tea waste—does not differ substantially from one another. Because NOx emissions are correlated with nitrogen content, reduced nitrogen indicates lower NOx emissions. (Sher *et al.,* 2017).

4.2. Energy Potential of Tea Waste and Sawdust

4.2.1. Tea Waste

The average calorific value of manufacturing tea waste was found to be 5.056 kWh/kg (18.206MJ/Kg) of tea waste. The calorific value of tea waste samples was evaluated using a bomb calorimeter. Similarly, when tea leaves and branches from collected garden waste samples were analyzed, the average calorific value was shown to be 4.303 kWh/kg, as indicated in Table 4.3.

Table 4. 3: Calorific value of tea bush waste

Type of garden waste	Calorific value (kWh/Kg)	Average calorific value (kWh/Kg)
Tea leaves	4.282	4.303
Branch of tea bush	4.324	

The energy potential from processing tea waste (approximately 1.91 x 10^5 kg) in Itona tea factory during the year 2021-2022 was calculated as 1.062 x 10^6 kWh as represented in Table 2. On the other hand, the energy obtainable from the garden tea bush pruned materials (leaves and branches) was estimated as 2.78 x 10^8kWh as shown in Table 4.4.

Table 4. 4: Energy potential of FTW

Parameters	Value
Annual tea production around Itona (kg)	9.550531×10^6
Tea waste (kg)	1.91×10^5
Calorific value (kWh/kg)	5.056
Energy potential (kWh)	1.062×10^6

Table 4. 5: Energy potential of garden tea bush waste

Parameters	Value
Tea plantation area around Itona tea factory (hectare)	4500
Spacing between rows (m)	1.05
Spacing between bushes (m)	0.70
Bush/area (m^2)	1.05 x 0.70 = 0.735
Bush/area (hectare)	10000/0.735 = 13605
Total number of bushes	13605 x 4500 = 6.12 x 10^7
Garden tea waste/bush/year (wet matter basis) (kg)	2.5
Garden tea waste/bush/ per year (dry matter basis) (kg)	1.05
Total garden tea waste (dry matter basis) (kg)	6.12 x 10^7 x 1.05 = 6.43 x 10^7
Calorific value of garden tea waste (kWh/kg)	4.303
Total energy production from garden tea waste (kWh)	2.78x10^8kWh

The available energy in waste generated from tea estates in Mufindi District was 3.26x10^8kWh. Energy conversion efficiency of calorific value to electrical energy was assumed to be 10%. The predicted total energy yield from tea estate wastes in terms of electrical energy was 3.26 x 107 kWh.

4.2.2. Saw Dust

As seen in Figure 4.4, the estimates were produced in the field in units of bags. The bulk density of the sawdust and the volume of the bags which was believed to be equal to the amount of the sawdust were then used to convert the estimations to mass quantities.

Figure 4. 4: 100 kg bags with sawdust

According to the equations provided in Sect. 3.2.3, the heating value of the sawdust is quantified as:

$HHV_{DB} = 20.08$ MJ/kg

Assuming the compositions of the combustible gas fractions of the syngas (Asibor et al., 2019) to be H = 18%, CO = 20%, and CH_4 = 2%, as elaborated in Eq. 9, the heating value of the obtainable syngas is

$LHV_{syngas} = 5.62\ MJ/m^3$

On average, a kilogram of dry biomass produces about 2–3 m^3 of syngas under standard conditions (Rajvanshi & Nimbkar, 2001).

Based on these findings electric power from sawdust and tea waste, respectively it is possible to conclude that the energy needs of the Itona tea factory might be substantially met by energy-value-adding the byproducts in addition to the plant. This illustrates how the tea processing sector may use its waste to generate electricity, making it somewhat self-sufficient, and using sawdust to make it entirely self-sufficient.

4.3. Optimum Ratio of The Mixture Between Tea Waste and Saw Dust

For these alternatives, 100g of the mixture was created, and the mass of the mixed sample was compared to the ratio of sawdust to tea trash. Proximate analysis of the mixing alternate ratios investigated in the laboratory is presented in Table 4.6.

Table 4. 6: proximate analysis of the mixture of sawdust and tea waste (%)

Mixing ratio (sawdust: tea waste)	Moisture content	Volatile Matter	Ash content	Fixed carbon	NCV
1:3	32	62	4.12	18.34	18.31
2:3	24	66	3.02	17.52	18.39
3:3	16	70	1.96	16.92	18.45

As it is seen in Figure 4.5(a), the 1:3 mixing ratio (saw dust: tea waste) has a slightly higher moisture content compared to other mixing ratios.

The fuel's energy worth decreases as the moisture content rises. Furthermore, a high moisture content in biomass feedstock is undesirable because it lowers the temperature during the oxidation process, which prevents the hydrocarbons inside a gasifier from fully breaking. For these reasons, the 3:3 sample performed well during gasification.

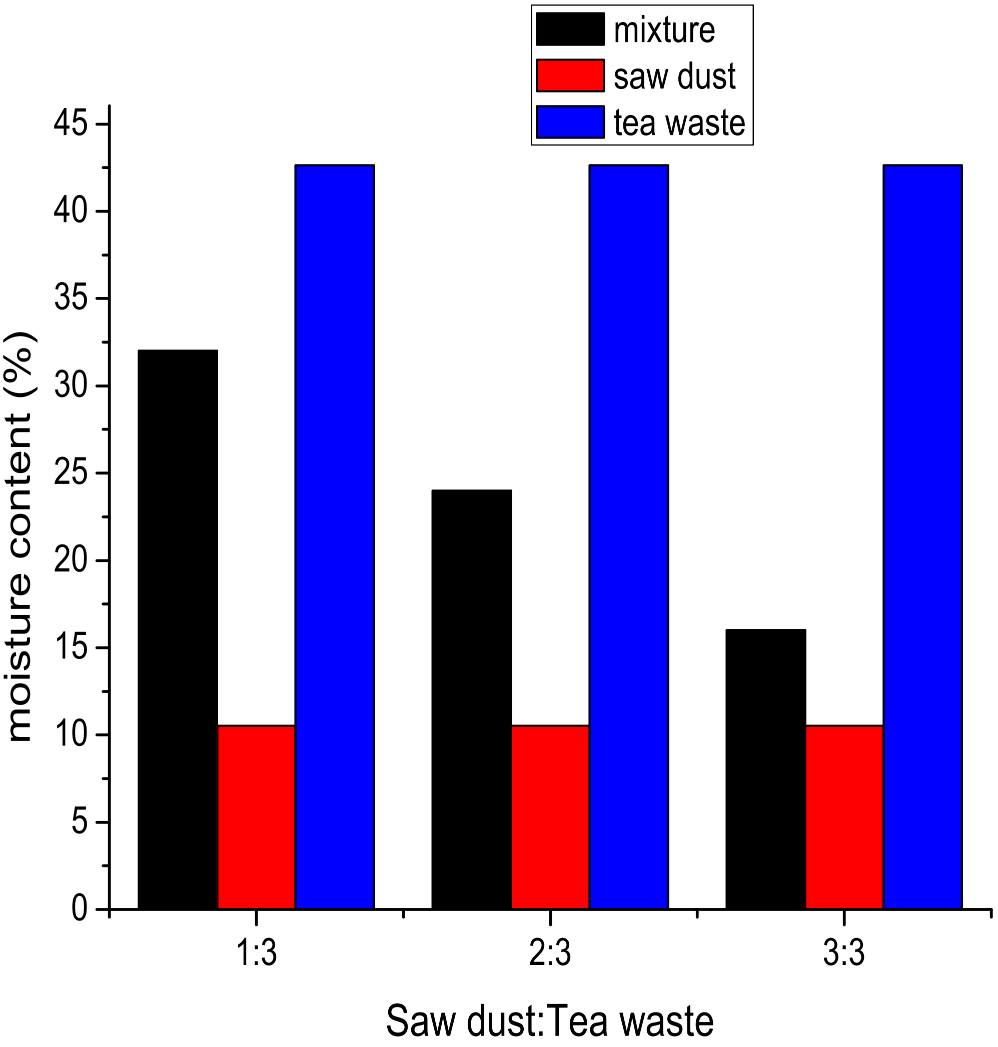

Figure 4.5 (a): Mixing ratio for saw dust and tea waste

The sample with a sawdust to tea waste ratio of 3:3 is likewise shown in Figure 4.5(a) to be more volatile than samples with other ratios of 1:3 and 2:3. Higher carbon conversion, cold gas efficiency, and syngas (CO and H2) concentration are implied by feedstock with a high volatile component.

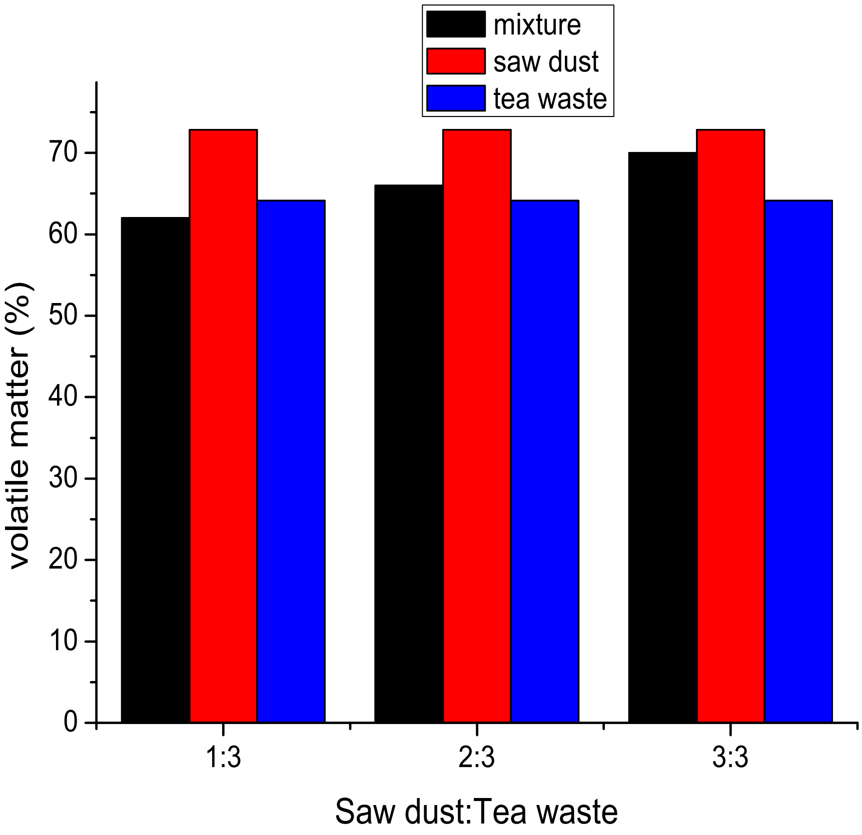

Figure 4.5 (b): Mixing ratio for saw dust and tea waste

In terms of ash, the sample with a mixing ratio of 1:3 is an ash-rich sample, having an ash concentration that is more than twice as high as the sample with a ratio of 3:3. The sample with a bark to sawdust ratio of 1:3 contains a higher amount of tea waste. There is more ash since the bark has a high mineral concentration. It's possible that some of the ash was contaminated with biomass, such as dirt, dust, soil, or other impurities.

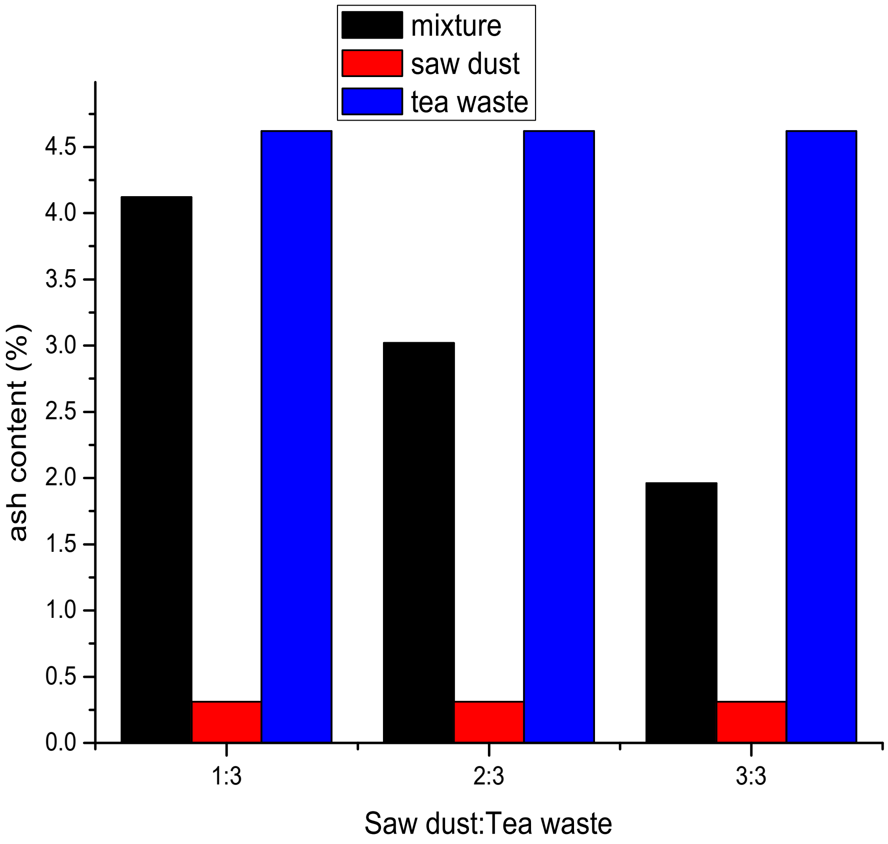

Figure 4.5 (c): Mixing ratio for saw dust and tea waste

Interestingly, the fixed carbon content of the 1:3 ratio is higher than that of the 2:2 and 3:3 ratios. The carbon in the burned residue left over after volatile matter has been removed is known as fixed carbon in biomass. The rate at which fixed carbon transforms into gases can be used to calculate the rate of gasification and the resulting product.

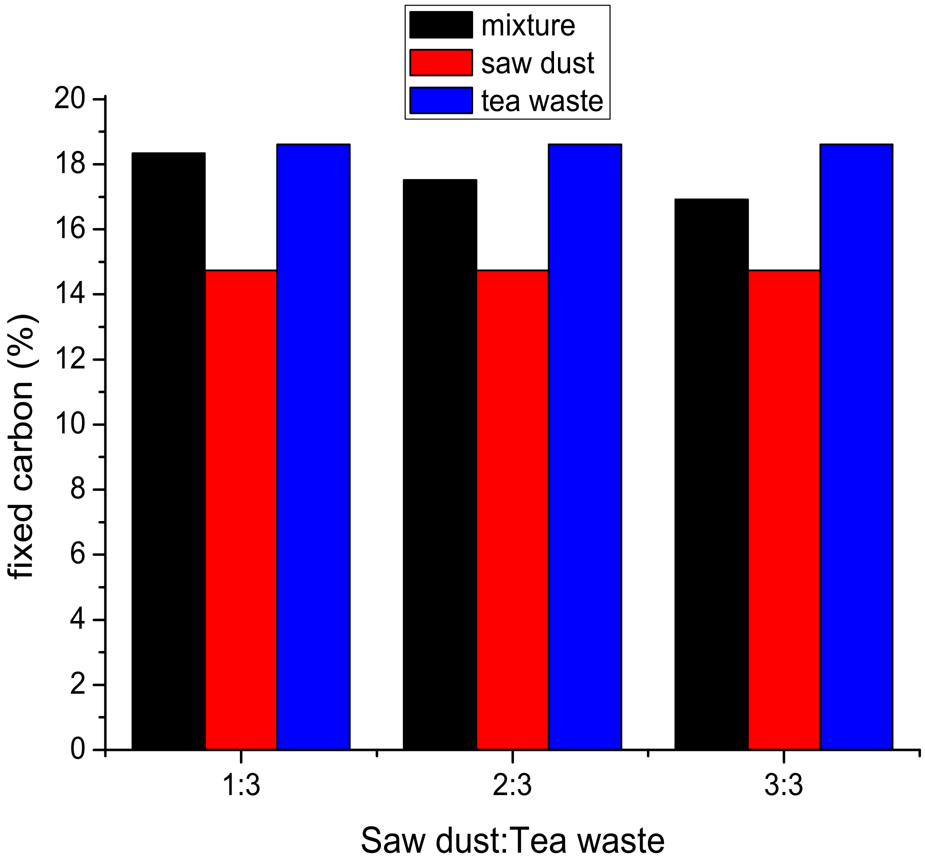

Figure 4.5 (d): Mixing ratio for saw dust and tea waste

4.4. Energy Consumption in Tea Factory

It was discovered that the production of tea requires between 3.5 and 7.5 kWh of energy per kilogram of tea. In regard to this, the total energy used to process 9.6 x 106 kg of tea from 4500 hectares of tea plantations surrounding Itona tea factory in Mufindi district during the year 2021–2022 was 4.32 x 107 kWh, of which the thermal energy used to produce each kg of tea was approximately 5.67 times greater than the electrical energy used, according to data from Mwenda (2016).

4.5. Energy Saving Using Tea Waste

From section 4.2 the available energy in waste generated from tea estates in Mufindi District was 3.26 x 10^8kWh. Energy conversion efficiency of calorific value to electrical energy was assumed to be 10%. From wastes on tea estates, an estimated total of electrical energy might be produced, amounting to 2.78 x 10^7 kWh. Hence, the total energy available from tea waste compared with total energy consumption annually during manufacturing of tea (4.32x10^7 kWh, 4.5 kWh/kg of made tea) shows that 64.4% amount of energy required in tea processing could be saved with the utilization (such as gasification technology) of tea waste generated from tea industries.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1. Conclusion

The study found that the tea waste and saw dust have calorific value ranging from 18.20 MJ/kg to 18.87 MJ/kg which indicates that they are suitable for various thermal application like gasification. The results also showed that the optimal mixture ratio of tea waste and sawdust is 3:3 which can produce a high yield of bioenergy. The fuel energy potential analysis of saw dust and tea waste also indicate potentially of being used as alternative fuel that could replace the use of wood fuel for tea drying. Therefore, upon gasification technology design environmental challenges associated with both wood fuel burning and tea waste disposal will be minimized.

5.2. Recommendation

Future sustainable energy supply should prioritize the building of a suitable gasifier for the sawdust and tea waste now accessible at Itona Tea Factory. Therefore, more research such as exergy analysis and gasifier design are advised for the proper design of waste to energy conversion technology.

REFERENCES

Aaqil, M., Peng, C., Kamal, A., Nawaz, T., Zhang, F., & Gong, J. (2023). *Tea Harvesting and Processing Techniques and Its Effect on Phytochemical Profile and Final Quality of Black Tea : A Review*. 1–28.

Abubakar, A. B., Maiduguri, R. P., Tela, B. M., & Oumarou, M. Ben. (2019). *Assessment of Biomass Gasification : A Review of Basic Design Considerations*. *February 2020*. https://doi.org/10.12691/ajer-7-1-1

AlNouss, A., Mckay, G., & Al-Ansari, T. (2018). Optimum Utilization of Biomass for the Production of Power and Fuels using Gasification. In *Computer Aided Chemical Engineering* (Vol. 43). Elsevier Masson SAS. https://doi.org/10.1016/B978-0-444-64235-6.50258-8

AlNouss, A., McKay, G., & Al-Ansari, T. (2020). Production of syngas via gasification using optimum blends of biomass. *Journal of Cleaner Production*, *242*, 118499. https://doi.org/10.1016/j.jclepro.2019.118499

Anjum, S. (n.d.). *Automation of Tea Processing Plant*.

Asibor, J. O., Akhator, E. P., & Obanor, A. I. (2019). Energy Potential Study of Some Tropical Wood Species from Nigeria. *Current Journal of Applied Science and Technology*, *37*(4), 1–10. https://doi.org/10.9734/cjast/2019/v37i430295

Barbuzza, E., Buceti, G., Pozio, A., Santarelli, M., & Tosti, S. (2019). Gasification of wood biomass with renewable hydrogen for the production of synthetic natural gas. *Fuel*, *242*(November 2018), 520–531. https://doi.org/10.1016/j.fuel.2019.01.079

Broer, K. M., & Peterson, C. (n.d.). *4 Gasification*.

Cai, J., He, Y., Yu, X., Banks, S. W., Yang, Y., Zhang, X., Yu, Y., Liu, R., & Bridgwater, A. V. (2017). Review of Physicochemical Properties and Analytical Characterization of Lignocellulosic Biomass (to be submitted to Renewable and Sustainable Energy Reviews). *Renewable and Sustainable Energy Review*, 1–50. https://research.aston.ac.uk/portal/files/21837510/Lignocellulosic_biomass_physicochemical_properties_and_analytical_characterization.pdf

Caillat, S., & Vakkilainen, E. (2013). Large-scale biomass combustion plants: An overview. In *Biomass Combustion Science, Technology and Engineering*. Woodhead Publishing Limited. https://doi.org/10.1533/9780857097439.3.189

Chan, E. W. C., Lim, Y. Y., Wong, S. K., Lim, K. K., Tan, S. P., Lianto, F. S., & Yong, M. Y. (2009). Effects of different drying methods on the antioxidant properties of leaves and tea of ginger species. *Food Chemistry*, *113*(1), 166–172. https://doi.org/10.1016/j.foodchem.2008.07.090

Chan, Y. H., Cheah, K. W., How, B. S., Loy, A. C. M., Shahbaz, M., Singh, H. K. G., Yusuf, N. R., Shuhaili, A. F. A., Yusup, S., Ghani, W. A. W. A. K., Rambli, J., Kansha, Y., Lam, H. L., Hong, B. H., & Ngan, S. L. (2019). An overview of biomass thermochemical conversion technologies in Malaysia. *Science of the Total Environment*, *680*, 105–123.

https://doi.org/10.1016/j.scitotenv.2019.04.211

Chhiti, Y., & Kemiha, M. (2013). Thermal Conversion of Biomass, Pyrolysis and Gasification. International Journal of Engineering and Science (IJES), 2(3), pp.75-85. *The International Journal of Engineering And Science*, *2*(3), 75–85. www.theijes.com

Chowdhury, A., Sarkar, S., Chowdhury, A., Bardhan, S., Mandal, P., & Chowdhury, M. (2016). Tea waste management: A case study from West Bengal, India. *Indian Journal of Science and Technology*, *9*(42). https://doi.org/10.17485/ijst/2016/v9i42/89790

Chua, L. Y. W., Chua, B. L., Figiel, A., Chong, C. H., Wojdyło, A., Szumny, A., & Łyczko, J. (2019). Drying of Phyla nodiflora leaves: Antioxidant activity, volatile and phytosterol content, energy consumption, and quality studies. *Processes*, *7*(4). https://doi.org/10.3390/pr7040210

Clauser, N. M., González, G., Mendieta, C. M., Kruyeniski, J., Area, M. C., & Vallejos, M. E. (2021). Biomass waste as sustainable raw material for energy and fuels. *Sustainability (Switzerland)*, *13*(2), 1–21. https://doi.org/10.3390/su13020794

Corredor, L., Patrice, P., & Bula, A. (2022). *Co-gasification of Biomass and Coal in a Top-Lit Updraft fixed bed gasifier : Syngas Composition and its Interchangeability with Natural Gas for Combustion Applications*. *316*.

Cowan-Gore, I., & Sein, T. T. (2020). *Myanmar Tea Cultivation and Processing Guide*. 73. https://www.ilo.org/wcmsp5/groups/public/---ed_emp/---

ifp_skills/documents/publication/wcms_742461.pdf

Deb, S., & Jolvis Pou, K. R. (2016). A Review of Withering in the Processing of Black Tea. *Journal of Biosystems Engineering*, *41*(4), 365–372. https://doi.org/10.5307/jbe.2016.41.4.365

Debnath, B., Haldar, D., & Purkait, M. K. (2021). Potential and sustainable utilization of tea waste: A review on present status and future trends. *Journal of Environmental Chemical Engineering*, *9*(5), 106179. https://doi.org/10.1016/j.jece.2021.106179

Devi, G. S., Vaishnavi, S., Srinath, S., Dutt, B., & Rajmohan, K. S. (2020). Chapter 19 - Energy recovery from biomass using gasification. In *Current Developments in Biotechnology and Bioengineering*. Elsevier B.V. https://doi.org/10.1016/B978-0-444-64321-6.00019-7

Dutta, P. P., & Baruah, D. C. (2014). Gasification of tea (Camellia sinensis (L.) O. Kuntze) shrubs for black tea manufacturing process heat generation in Assam, India. *Biomass and Bioenergy*, *66*, 27–38. https://doi.org/10.1016/j.biombioe.2014.03.062

Efficiency, E., & Solutions, R. E. (n.d.). *Improving the Energy Supply for Ugandan Tea factories*. 1–5.

Gomaa, M. R., Matarneh, G. A., Shalby, M., & AL-Rawashdeh, H. A. (2020). A State of the art Review on a Thermochemical Conversion of Carbonaceous Materials: Production of Synthesis Gas by Co-Gasification Process-Part I. *Current Alternative Energy*, *4*(1), 26–46.

https://doi.org/10.2174/2405463104999200904115100

Gunawan, Y., Putra, N., Hakim, I. I., Agustina, D., & Mahlia, T. M. I. (2021). Withering of tea leaves using heat pipe heat exchanger by utilizing low-temperature geothermal energy. *International Journal of Low-Carbon Technologies*, *16*(1), 146–155. https://doi.org/10.1093/ijlct/ctaa041

Gupta, R., & Dey, S. K. (2010). Development of a productivity measurement model for tea industry. *Journal of Engineering and Applied Sciences*, *5*(12), 16–25.

Gururani, P., Bhatnagar, P., Bisht, B., Jaiswal, K. K., Kumar, V., Kumar, S., Vlaskin, M. S., Grigorenko, A. V., & Rindin, K. G. (2022). Recent advances and viability in sustainable thermochemical conversion of sludge to bio-fuel production. *Fuel*, *316*(December 2021), 123351. https://doi.org/10.1016/j.fuel.2022.123351

Hasanuzzaman, M., & Technologies, P. (n.d.). *Agronomic Crops* (Vol. 1).

Hossain, S. M. Z. (2019). Biochemical Conversion of Microalgae Biomass into Biofuel. *Chemical Engineering and Technology*, *42*(12), 2594–2607. https://doi.org/10.1002/ceat.201800605

Jaiswal, K. K., Dutta, S., Banerjee, I., Pohrmen, C. B., & Kumar, V. (2023). Photosynthetic microalgae–based carbon sequestration and generation of biomass in biorefinery approach for renewable biofuels for a cleaner environment. *Biomass Conversion and Biorefinery*, *13*(9), 7403–7421. https://doi.org/10.1007/s13399-021-01504-y

Janajreh, I., Adeyemi, I., Raza, S. S., & Ghenai, C. (2021). A review of recent developments and future prospects in gasification systems and their modeling. *Renewable and Sustainable Energy Reviews*, *138*(February), 110505. https://doi.org/10.1016/j.rser.2020.110505

Jayah, T. H. (2002). *EVALUATION OF A DOWNDRAFT WOOD GASIFIER FOR TEA MANUFACTURING IN SRI LANKA*. *March*.

Jayasinghe, S. L., & Kumar, L. (2021). Potential impact of the current and future climate on the yield, quality, and climate suitability for tea [camellia sinensis (L.) O. Kuntze]: A systematic review. *Agronomy*, *11*(4). https://doi.org/10.3390/agronomy11040619

Kamunya, S., & Ochanda, S. (2019). *Tea Growers Guide*.

Kanwar, A. (2023). *Comprehensive review on tea processing*. *12*(5), 1995–2002.

Kilel, E. C. (2019). *Optimization of brewing, processing conditions and their effects on the chemical and sensory quality of purple-leafed kenyan tea*.

Kumar, S. (2016). *Asian Journal of Agriculture and Rural Development ASSESSMENT OF BIO-ENERGY POTENTIAL IN TEA INDUSTRIES OF INDIA*. *6*(5), 83–89. https://doi.org/10.18488/journal.1005/2016.6.5/1005.5.83.89

Kumar, S., Nilling, J. J., Imchen, L., Bhutia, P. L., & Pranav, P. K. (2014). Estimation of its waste and energy potential in Tea estate of Assam. *Aspects of Mechanical Engineering and Technology for Industry*, *4*(December).

Kumarihami, H. M. P. C., & Song, K. J. (2020). *Review on Challenges and*

Opportunities in Global Tea Industry. *September 2018*. https://doi.org/10.29225/jkts.2018.24.3.79

Lee, S. Y., Sankaran, R., Chew, K. W., Tan, C. H., Krishnamoorthy, R., Chu, D.-T., & Show, P.-L. (2019). Waste to bioenergy: a review on the recent conversion technologies. *BMC Energy*, *1*(1), 1–22. https://doi.org/10.1186/s42500-019-0004-7

Lenz, V., Szarka, N., Jordan, M., & Thrän, D. (2020). Status and Perspectives of Biomass Use for Industrial Process Heat for Industrialized Countries. *Chemical Engineering and Technology*, *43*(8), 1469–1484. https://doi.org/10.1002/ceat.202000077

Liu, H., & Kojima, T. (2004). Theoretical study of coal gasification in a 50 ton/day HYCOL entrained flow gasifier. II. Effects of operating conditions and comparison with pilot-scale experiments. *Energy and Fuels*, *18*(4), 913–917. https://doi.org/10.1021/ef030163j

Loha, C., Karmakar, M. K., De, S., & Chatterjee, P. K. (2018). Gasifiers: Types, Operational Principles, and Commercial Forms. *Energy, Environment, and Sustainability*, 63–91. https://doi.org/10.1007/978-981-10-7335-9_3

Mallik, P. (2021). *Impact of Climate on Tea Production : A Study of the Dooars Region in India Impact of Climate on Tea Production : A Study of the Dooars*.

Mazaheri, N., Akbarzadeh, A. H., Madadian, E., & Lefsrud, M. (2019). Systematic review of research guidelines for numerical simulation of biomass gasification for bioenergy production. *Energy Conversion and Management*, *183*(February), 671–688. https://doi.org/10.1016/j.enconman.2018.12.097

Mckendry, P. (2002). *Energy production from biomass (part 3): gasification technologies*. *83*(July 2001), 55–63.

Merrett, K. M., & Whitty, K. J. (2019). *Evaluation of coal conversion pathways in fluidized bed chemical looping combustion with oxygen uncoupling (CLOU) 3*.

Muh, E., Tabet, F., & Amara, S. (2019). Biomass Conversion to Fuels and Value-Added Chemicals: A Comprehensive Review of the Thermochemical Processes. *Current Alternative Energy*, *4*(1), 3–25. https://doi.org/10.2174/2405463103666191022121648

Muoki, C. R., Maritim, T. K., Oluoch, W. A., Kamunya, S. M., & Bore, J. K. (2020). Combating Climate Change in the Kenyan Tea Industry. *Frontiers in Plant Science*, *11*(March), 1–10. https://doi.org/10.3389/fpls.2020.00339

Mwenda, I. J., Ngugi, K. J., & Jeremiah, K. (2015). *Technology & Research Energy Consumption Trends In Smallholder Tea Factories In Kenya*. *2*(2), 30–43.

Mwenda, J. I. (2016). Analysis of energy utilization and renewable energy potential in KTDA region two tea factories in Kenya kenyatta university. *Master of Science Degree in Energy Technology*.

Njenga, M., & Iiyama, M. (2017). *How briquettes are saving Makomboki tea factory millions in energy costs*. *July*.

Nzali, B. T., Mvogo, P. O., Ali, A., & Mouangue, R. (2019). Effect of particle size on syngas production using sawdust of Cameroonian Triplochiton scleroxylon.

Scientific African, *6*, e00182. https://doi.org/10.1016/j.sciaf.2019.e00182

Orjales, I., Herrero-Latorre, C., Miranda, M., Rey-Crespo, F., Rodríguez-Bermúdez, R., & López-Alonso, M. (2018). Evaluation of trace element status of organic dairy cattle. *Animal*, *12*(6), 1296–1305. https://doi.org/10.1017/S1751731117002890

Ouwens, D. (2023). *Gasification of biomass and residues for electricity production Pergamon*. *12*(1997), 387–407. https://doi.org/10.1016/S0961-9534(97)00010-X

Owuor, P. O., Kamau, D. M., Kamunya, S. M., Msomba, S. W., Uwimana, M. A., Okal, A. W., & Kwach, B. O. (2011). *Effects of Genotype , Environment and Management on Yields and Quality of Black Tea*. https://doi.org/10.1007/978-94-007-1521-9

Pang, S. (2019). Advances in thermochemical conversion of woody biomass to energy, fuels and chemicals. *Biotechnology Advances*, *37*(4), 589–597. https://doi.org/10.1016/j.biotechadv.2018.11.004

Park, B., Park, S., & Park, S. (2022). *A Study on Applying PID Control to a Downdraft Fixed Bed Gasifier using Wood Pellets*. 149–159.

Parraga, J., Khalilpour, K. R., & Vassallo, A. (2018). Polygeneration with biomass-integrated gasification combined cycle process: Review and prospective. *Renewable and Sustainable Energy Reviews*, *92*(October 2016), 219–234. https://doi.org/10.1016/j.rser.2018.04.055

Piyathissa, S., Kahandage, P., Dissanayake, P., & Rambanda, M. (2020). *Selective*

Tea Plucking Machine to Reduce The Labor Involvement Selective Tea Plucking Machine to Reduce The Labor Involvement. *May*, 142–149.

Pou, K. R. J., Paul, S. K., & Malakar, S. (2019). Industrial processing of CTC black tea. In *Caffeinated and Cocoa Based Beverages: Volume 8. The Science of Beverages*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-815864-7.00004-0

Prakash, H., Doherty, D. O., & Bittenbender, H. C. (2011). Farm and Forestry Production and Marketing Profile for Cacao. *Permanent Agriculture Resouces*, 23.

R.K.M.D.S, M.B.D.K, S., B.M.P.D.K.R, S., & B.M.P.N, B. (2020). Environmental Pollution by Tea Processing. *Journal of Research Technology & Engineering*, *1*(4), 95–104. https://www.jrte.org/wp-content/uploads/2020/10/Environmental-Pollution-By-Tea-Processing.pdf

Rahman, A., Sudarmanta, B., Fansuri, H., & Muraza, O. (n.d.). *Syngas Production from Municipal Solid Waste with a Reduced Tar Yield by Three-Stages of Air Inlet to a Downdraft Gasifier*.

Rajvanshi, A. K. (1986). Biomass gasification in: Alternative Energy in Agriculture. *Alternative Energy in Agriculture*, *2*(4), 83–102.

Rajvanshi, A. K., & Nimbkar, N. (2001). Sweet sorghum R&D at the Nimbkar Agricultural Research Institute (NARI). *Nimbkar Agricultural Research Institute*, *November 2016*, 1–10. http://nariphaltan.virtualave.net/sorghum.htm%5Cnfile://c/Documents and Settings/Danie/My Documents/Reference Manager/241 Sweet Sorghum RD at

NARI.htm

Reygaert, W. C. (2018). *Green Tea Catechins: Their Use in Treating and Preventing Infectious Diseases*. *2018*.

Saeed, M., Naveed, M., Arif, M., Kakar, M. U., Manzoor, R., Abd El-Hack, M. E., Alagawany, M., Tiwari, R., Khandia, R., Munjal, A., Karthik, K., Dhama, K., Iqbal, H. M. N., Dadar, M., & Sun, C. (2017). Green tea (Camellia sinensis) and L-theanine: Medicinal values and beneficial applications in humans—A comprehensive review. *Biomedicine and Pharmacotherapy*, *95*(July), 1260–1275. https://doi.org/10.1016/j.biopha.2017.09.024

Safarian, S., Unnþórsson, R., & Richter, C. (2019). A review of biomass gasification modelling. *Renewable and Sustainable Energy Reviews*, *110*(August), 378–391. https://doi.org/10.1016/j.rser.2019.05.003

salvatian, saeeyed babak, majd salimi, kourosh, & Javadi, A. (2018). Energy Consumption in Processing of Black Tea in Tea Factories. *Agricultural Mechanization and Systems Research*, *19*(71), 29–42. https://doi.org/10.22092/erams.2017.106506.1100

Sarafraz, M. M., Safaei, M. R., Jafarian, M., Goodarzi, M., & Arjomandi, M. (2019). High quality syngas production with supercritical biomass gasification integrated with a water–gas shift reactor. *Energies*, *12*(13). https://doi.org/10.3390/en12132591

Shankarpure, M. R., & Patil, D. D. (2023). *INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING A Comprehensive Survey on Methods and*

Techniques for Automated Fruit Plucking. 0–1.

Shao, C., Zhang, C., Lv, Z., & Shen, C. (2021). *Scientia Horticulturae Pre- and post-harvest exposure to stress influence quality-related metabolites in fresh tea leaves (Camellia sinensis)*. *281*(January).

Sharma, A., Dutta, A. K., Bora, M. K., & Dutta, P. P. (2019). Study of energy management in a tea processing industry in Assam, India. *AIP Conference Proceedings*, *2091*(April 2019). https://doi.org/10.1063/1.5096503

Sharma, A., & Dutta, P. P. (2018). Scientific and technological aspects of tea drying and withering: A review. *Agricultural Engineering International: CIGR Journal*, *20*(4), 210–220.

Sharma, P., Gupta, B., Pandey, M., Singh, K., & Baredar, P. (2020). Materials Today : Proceedings Downdraft biomass gasification : A review on concepts , designs analysis , modelling and recent advances. *Materials Today: Proceedings*, *xxxx*. https://doi.org/10.1016/j.matpr.2020.08.789

Sharma, P., Kaur, H., Sharma, M., & Sahore, V. (2011). A review on applicability of naturally available adsorbents for the removal of hazardous dyes from aqueous waste. *Environmental Monitoring and Assessment*, *183*(1–4), 151–195. https://doi.org/10.1007/s10661-011-1914-0

Sher, F., Pans, M. A., Afilaka, D. T., Sun, C., & Liu, H. (2017). Experimental investigation of woody and non-woody biomass combustion in a bubbling fluidised bed combustor focusing on gaseous emissions and temperature profiles. *Energy*, *141*, 2069–2080. https://doi.org/10.1016/j.energy.2017.11.118

Shreyash, N., Sonker, M., Bajpai, S., Tiwary, S. K., Khan, M. A., Raj, S., Sharma, T., & Biswas, S. (2021). The review of carbon capture-storage technologies and developing fuel cells for enhancing utilization. *Energies*, *14*(16). https://doi.org/10.3390/en14164978

Suyanto, Surana, T., Atmojo, J. P., & Prasetyo, B. T. (2010). Design of a Geothermal Energy Dryer for Tea Withering and Drying in Wayang Windu Geothermal Field. *Proceedings World Geothermal Congress*, *April*, 25–29.

T. R. Dias, Tomás, G., Teixeira, N. F., Alves, M. G., Oliveira, P. F., & Silva, B. M. (2013). White Tea (Camellia Sinensis (L.)): Antioxidant Properties And Beneficial Health Effects. *International Journal of Food Science, Nutrition and Dietetics*, *2*(2), 19–26.

Taulo, J. L., & Sebitosi, A. B. (2015). Energy consumption analysis for the Malawian tea industry. *Proceedings of the Conference on the Industrial and Commercial Use of Energy, ICUE*, *2015-Septe*, 191–198. https://doi.org/10.1109/ICUE.2015.7280268

Taulo, J. L., & Sebitosi, A. B. (2016). Material and energy flow analysis of the Malawian tea industry. *Renewable and Sustainable Energy Reviews*, *56*, 1337–1350. https://doi.org/10.1016/j.rser.2015.11.072

Teshome, K. (2019). Effect of tea processing methods on biochemical composition and sensory quality of black tea (Camellia sinensis (L.) O. Kuntze): A review. *Journal of Horticulture and Forestry*, *11*(6), 84–95. https://doi.org/10.5897/JHF2019.0588

Thirunavukkarasu, M., & Sawle, Y. (2022). An Examination of the Techno-Economic Viability of Hybrid Grid-Integrated and Stand-Alone Generation Systems for an Indian Tea Plant. *Frontiers in Energy Research*, *10*(March), 1–30. https://doi.org/10.3389/fenrg.2022.806870

Tursi, A. (2019). A review on biomass: Importance, chemistry, classification, and conversion. *Biofuel Research Journal*, *6*(2), 962–979. https://doi.org/10.18331/BRJ2019.6.2.3

Valderrama Rios, M. L., González, A. M., Lora, E. E. S., & Almazán del Olmo, O. A. (2018). Reduction of tar generated during biomass gasification: A review. *Biomass and Bioenergy*, *108*(July 2017), 345–370. https://doi.org/10.1016/j.biombioe.2017.12.002

Vishnoi, H., Bodla, R., Kant, R., & Bodla, R. B. (2018). Green Tea (Camellia Sinensis) and Its Antioxidant Property: a Review. *Article in International Journal of Pharmaceutical Sciences and Research*, *9*(5), 1723. https://doi.org/10.13040/IJPSR.0975-8232.9(5).1723-36

Wazeer, A., & Dubey, K. K. (2018). *Technological Review on Biomass Gasification Models Technological Review on Biomass Gasification Models*. *December*.

Wu, H., Chen, Y., Feng, W., Shen, S., Wei, Y., Jia, H., Wang, Y., Deng, W., & Ning, J. (2022). Effects of Three Different Withering Treatments on the Aroma of White Tea. *Foods*, *11*(16). https://doi.org/10.3390/foods11162502

Xia, J., Guo, Z., Fang, S., Gu, J., & Liang, X. (2021). Effect of Drying Methods on Volatile Compounds of Burdock. *Foods*, *70*(868), 1–17.

Xiang, X., Gong, G., Wang, C., & Cai, N. (2020). *Exergy analysis of updraft and downdraft fixed bed gasification of village- level solid waste ScienceDirect Exergy analysis of updraft and downdraft fixed bed gasification of village-level solid waste*. *July 2022*. https://doi.org/10.1016/j.ijhydene.2020.09.247

Xu, D., Zhang, Y., Hsieh, T. L., Guo, M., Qin, L., Chung, C., Fan, L. S., & Tong, A. (2018). A novel chemical looping partial oxidation process for thermochemical conversion of biomass to syngas. *Applied Energy*, *222*, 119–131. https://doi.org/10.1016/j.apenergy.2018.03.130

Zhang, L., Xu, C. (Charles), & Champagne, P. (2010). Energy recovery from secondary pulp/paper-mill sludge and sewage sludge with supercritical water treatment. *Bioresource Technology*, *101*(8), 2713–2721. https://doi.org/10.1016/j.biortech.2009.11.106

Zhang, Y., Cui, Y., Chen, P., Liu, S., Zhou, N., Ding, K., Fan, L., Peng, P., Min, M., Cheng, Y., Wang, Y., Wan, Y., Liu, Y., Li, B., & Ruan, R. (2019). Gasification technologies and their energy potentials. In *Sustainable Resource Recovery and Zero Waste Approaches*. Elsevier B.V. https://doi.org/10.1016/B978-0-444-64200-4.00014-1

Zohuri, B., & Future, C. (n.d.). *Bahman Zohuri (2019) Hydrogen Energy: Challenges and Solutions for a Cleaner Future. Springer Nature Switzerland AG, ISBN 978-3-319-93461-7 (eBook).*