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Full Length Research Paper

Development and Testing of a Novel Pilot-Scale Solar Pyrolysis Reactor

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ABSTRACT: Thermochemical conversion methods such as gasification and pyrolysis have shown promise in harnessing solar energy. The feedstock in the reactor is heated using biomass or an electric run heater in the traditional pyrolysis method. This eventually leads to excessive energy use and the emission of greenhouse gases (GHG). Solar-assisted pyrolysis would be one of the solutions to the pyrolytic reactor's heating problem. This study created and tested a unique pyrolysis system that used solar energy for pre-heating. Three Fresnel lenses were tested to determine the viability of using solar energy into a pyrolysis system. The innovative system's test results were compared to those of the standard pyrolysis system. In comparison to the standard pyrolysis system, the solar-assisted system has lower fuel costs, energy usage, and GHG output. Under the current energy crisis, this technique as a supplement to fossil fuels requires increased attention.

Keywords: Biomass conversion, solar thermal applications, pyrolysis, reactor, fresnel lens

INTRODUCTION

Energy and waste management are two of the most critical challenges to solve as part of the growing urge to address the acceleration of climate change while balancing the demand for growth in emerging nations (Caputo and Maek, 2021; Gasser, T et al., 2018). The IEA has regularly linked energy availability and electrification to the Sustainable Development Goals (SDGs). As a result, they are increasingly being studied jointly in order to help developing countries reduce the effects of climate change (Hirmer et al. 2014, WEO-2017).

It is estimated that 1.1 billion people still do not have access to electricity, while 2.8 billion continue to rely on conventional biomass combustion for cooking or heating demand, owing mostly to unsustainable forestry practices or consumption. Sub-Saharan Africa (SSA) is predicted to be the region most severely affected by changing climate conditions due to particularly vulnerable climate conditions, low development levels, and the existing lack of proper policy frameworks (Akram et al., 2019; Ndukwu et al., 2021). While it is expected that the number of people without access to electricity will fall to 674 million by 2030, 600 million of those are expected to live in rural parts of SSA, which now has a 43 percent electrification rate (IEA. WEO-2017). Given the abundance of feedstock, bioenergy has been identified as one of the most feasible energy access pathways in the region; however, its scale deployment has thus far been primarily limited by technical capacity, concerns about competition with food crops, and cultural acceptance considerations (Caputo and Maek, 2021). Traditional bioenergy systems present significant disadvantages regarding the quality of the provision of energy services relative to the economic and energetic expenditure. They typically exhibit very low efficiencies of 5–20% and can only supply low-grade heat with limited control methods (Lynd et al., 2015).

Because of the low material energy density, a large

amount of biomass is required to meet daily demands, resulting in women and children spending up to 8 hours a day collecting material in some communities, with negative externalities on deforestation (Caputo and Maek, 2021; K. C. Das et al., 2011; Tucho and Nonhebel, 2015). Furthermore, it is predicted that 350,000 children and 34,000 adult women die each year as a result of health problems connected with indoor and polluted bioenergy usage (Lynd et al., 2015; Mertz et al., 2009).

With the rising cost of conventional energy such as LPG, DPK, and PMS, fuelwood has been increasingly commercialised as an energy source, with about 68% of rural and sub-urban households in the country which cannot access the fuelwood from the forest buying from the fuelwood market (Baiyegunhiand Hassan, 2014). Climate change adaptation has become a critical issue that cannot be separated from the demands of Nigerian households for energy. Therefore, a viable power system needs to be developed to curb the increasing power deficiency and combat the impacts of climate change. Globally, renewable energy technologies are becoming increasingly popular and applicable. This includes solar, biomass, wind, and hydropower. As a primary source of energy, solar energy has gained considerable ground. A vital part of the solar energy system is biomass, and its waste can be utilised in the pyrolysis process.

Waste biomass is a potentially more helpful renewable resource that can be used effusively as a principal heat source for cooking and can correspondingly subsidise the production of energy, heat, biofuels, and chemicals like solid fuel, including char or carbon. Waste residues are mixed and burned with coal to produce electricity. Presently, crude oil is substituted by bioethanol and biodiesel derived from a biomass substrate. Biomass can be made from a specific class of chemicals that can subsequently replace the use of non-renewable oil and coal resources. An enormous variety of products can be extracted from biomass, leading to studies using various forms of thermal conversion technologies, including pyrolysis, gasification, torrefaction, anaerobic digestion, and hydrothermal processing. Hundreds of years ago, pyrolysis of woody biomass was initiated to acquire pyroligneous acid, versatile applications.

To increase the energy density of the waste residues, technological improvement and process condition modification may give an acceptable, environmentally benign scheme. Pyrolysis is considered to be the primary method to extract renewable energy (bio-oil) from different kinds of biomass, including agricultural residues and forest residues, and pyrolysis is deemed to be the primary method of extracting renewable energy (bio-oil) from other types of biomass including agricultural residues, forest residues, and municipal waste. Pyrolysis, a thermal decomposition process of organic components in biomass wastes in the absence of oxygen at mediate temperature (about 500◦C), provides yield products tar (bio-oil, biofuel, and biocrude), char (activated carbon), and gaseous fractions (fuel gases) municipal waste. Pyrolysis, a thermal decomposition process of organic components in biomass wastes in the absence of oxygen at mediate temperature (about 500◦C), provides yield products tar (bio-oil, biofuel, and biocrude), char (activated carbon), and gaseous fractions (fuel gases). This research provides insights into the reaction stages during pyrolysis and the result of the products' reaction conditions.

Objectives

This research was aimed at the following purposes:

Design of the novel pilot-scale solar pyrolysis plant
Construction of the pyrolysis plant
Multi-parameter measurement of the biomass solar pyrolysis process if it provides an appropriate renewable energy source,

Energy scenarios from pyrolysis

The current worldwide supply of energy is primarily based on fossil fuels (petroleum, natural gas, coal), the reserves of which are finite. Fossil fuel in Nigeria is projected to extinction in about thirty years. This raises great concern because sales made from crude oil export are her economy's mainstay (Chukwuezie et al., 2018). Given the growing world population, rising per capita energy consumption, and proof of global warming, there is a clear need for long-term alternative energy sources (Mohammed et al., 2012; Chukwuezie et al., 2018). In the context of current energy scenarios, biomass is a promising, eco-friendly alternative renewable energy source. Biomass can be converted to biofuel through various thermal, biological, and physical processes. Pyrolysis has attracted more interest in producing liquid fuel products due to its advantages in storage, transport, and application versatility, such as combustion engines, boilers, turbines, etc., among the biomass to energy conversion processes (Mohammed *et al.*, 2012).

Pyrolysis is defined as the thermal decomposition of biomass (lignocellulosic derivatives) under an inert condition in an oxygen-deficient environment. The word results from two Greek words: 'pyro,' which means fire, and 'lysis,' which implies disintegration into integral parts. Pyrolysis technology is ancient, and earlier it was first used to prepare charcoal in the Middle East and Southern Europe before 5500 years ago(Zaman et al., 2017). Egyptian people used this technique to produce tar for sealing boats(Zaman et al., 2017). Subsequently, the practice of pyrolysis processes has been growing and is extensively carried out for charcoal and coke fabrication.
Various thermochemical and biological processes have been adopted to turn biomass into value-added products. Pyrolysis is more convenient among these processes as it has many advantages of storage, transport, and

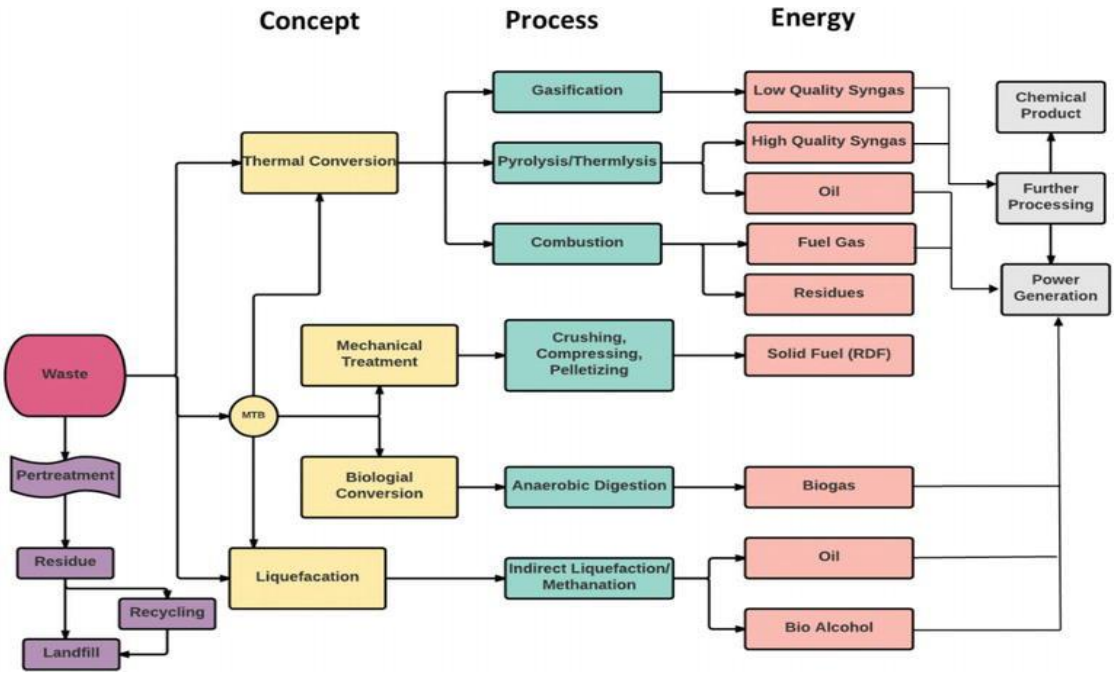

Figure 1. The biomass conversion process to obtain value-added products Zaman et al. (2017).

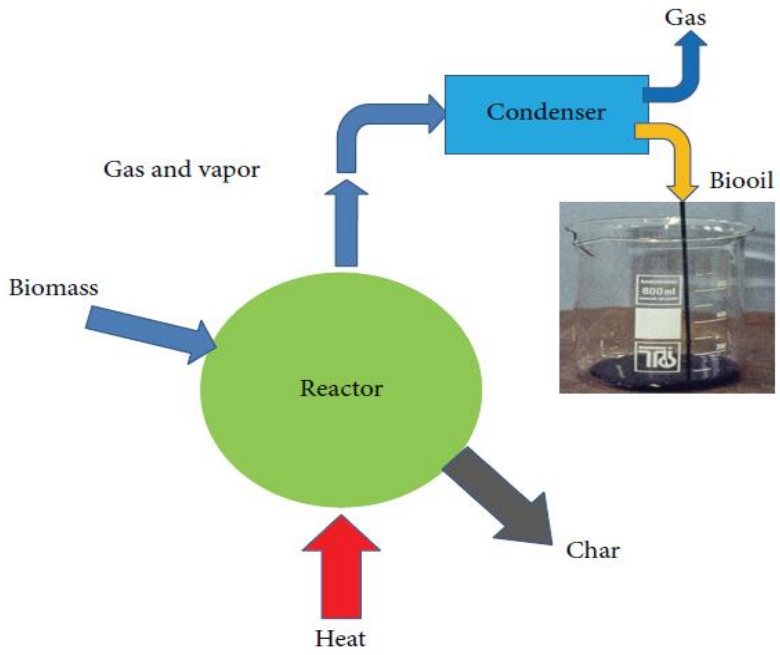

Figure 2: A possible pathway of pyrolysis of organic solid waste (Joardder et al., 2014).

solicitation versatility, such as generators, combustion appliances, boilers, engines, etc. Solid biomass and waste are especially difficult for pyrolysis research to process in some instances. In terms of expansion, it is so far at a preliminary stage and still needs to overcome various functional barriers to dealing with traditional fossil fuel-centered processes(Zaman et al., 2017). The current biomass conversion process forms with their respective production are shown in (Figures 1-2).

A pyrolysis system unit typically includes lignocellulosic residue pre-processing equipment, the pyrolysis reactor, and the matching downstream processing unit (Joardder et al., 2014; Tucho and Nonhebel, 2015). It is primarily described as units that generate simply heat and biochar

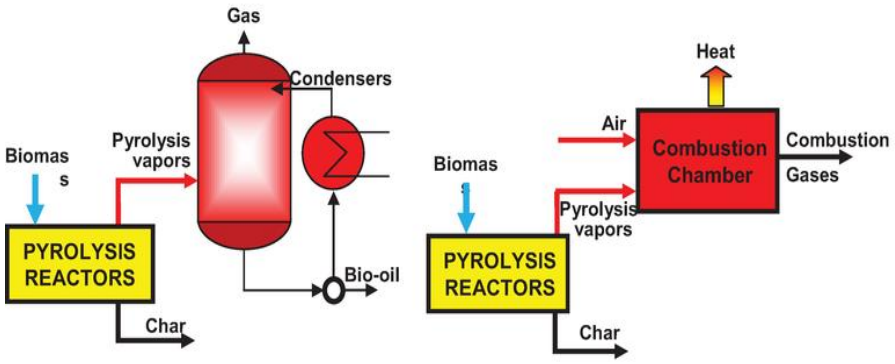

Figure 3. Simplified flow diagram for a typical pyrolysis unit. (a) Biochar and bio-oil production. (b) Biochar and heat production. (Zaman et al., 2017).

Pyrolysis type	Process conditions			Product yields		
	Heating rate, β	Process time, τ	Temperature, T	Solid	Liquid	Gas
Slow	< 50 K·min^{-1}	5-30 min	400-600 °C	<35 %	<30 %	<40 %
Fast	10-200 K·s^{-1}	< 5 s	400-600 °C	<25 %	<75 %	<20 %
Flash	~1,000 K·s^{-1}	< 0.1 s	600-900 °C	<20 %	<20 %	<70 %

Table 1: Pyrolysis technologies classification (Sobek and Werle, 2019).

(through slow pyrolysis) or biochar and bio-oils (by fast pyrolysis). Figure 3 depicts the fundamental arrangement of pyrolysis units and their important products.

Types of pyrolysis

Pyrolysis is the primary method to extract renewable energy (bio-oil) from different kinds of biomass, including agricultural residues, forest residues, and municipal waste. Pyrolysis, a thermal decomposition process of organic components in biomass wastes in the absence of oxygen at mediate temperature (500◦C), provides yield products tar (bio-oil, biofuel, and biocrude), char (activated carbon), and gaseous fractions (fuel gases) (Joardder et al., 2014). Pyrolysis processes can be categorized as slow Pyrolysis, flash and fast Pyrolysis based on the time it takes to complete thermal decomposition of the feed materials.

Table 1 shows significant pyrolysis technologies' specifications, process parameters, and estimated product yields(Sobek and Werle, 2019). Slow pyrolysis, characterized by the most extended reaction times and lowest heating rates, results in relatively uniform product distribution, with a slight skew towards higher char yields(Joardder et al., 2014; Sobek and Werle, 2019). A longer reaction time favours char formation and secondary reactions, like the cracking and reforming of tar, which increases the final solid yield(Joardder et al., 2014). Fast pyrolysis is widely used as it takes seconds to complete the decomposition of biomass and produces about 60% of the yield as bio-oil. In contrast, slow pyrolysis results in biochar as the main product and takes several hours to complete(Joardder et al., 2014). However, the particle size of feedstocks affects the efficiency and nature of the pyrolysis process.

In addition, pyrolysis can be fixed bed pyrolysis or fluidized bed pyrolysis. A fixed bed pyrolyser is used in fixed bed pyrolysis, where the feed material is placed in the reactor and heated to a high temperature (Joardder et al., 2014; Sobek and Werle, 2019). To create inert conditions, inert gas (typically nitrogen) must be used, and the gaseous mixture must be disposed of into the condenser.

The diagram depicts a hypothetical pyrolysis process pathway (Figure 2). This technology is spreading through research and experimentation in various countries throughout the world (Joardder et al., 2014; Lynd et al., 2015). Biomass can be used as a starting source for

Table 2: Phytochemical analysis of Gmelina Arborea

Phytochemical	concentration (Mg/100g)
Tannins	0.06± 0.00
Saponins	3.85± 0.000
Glycosides	1.77± 0.06
Flavonoid	0.06± 0.01
Alkaloids	0.06± 0.00
Phenols	0.32± 0.00
Steroids	0.09± 0.00

Table 3: Proximate composition of Gmelina Arborea

Proximate	percentage composition (%)
Moisture	12.35± 0.52
Fat	0.79± 0.02
Ash	4. 55± 0.49
Crude fibre	15.05± 0.07
Protein	20.05± 0.07
Carbohydrate	47.22± 1.04

The proximate analysis estimates and determines the significant components, i.e., moisture, fats, proteins, ash, and crude fibre in a given food.

pyrolysis, which produces liquid, gaseous, and solid fuels. Pyrolysis conversion technique for biomass has been studied for three decades and is now commercially available (Akram et al., 2019).

The technology generates gas, vapour, and solid char; however, the proportion of the yield products is determined by the types and qualities of feed materials as well as the process parameters (Joardder et al., 2014). Solid char with a GCV of 17–36MJ/kg can be used to supply heat for the pyrolysis process, as a fuel either directly as briquettes or as char-oil, and as feedstock to manufacture activated carbon. The pyrolysis gas component contains CO_2, CO, H_2, CH_4, C_2H_4, C_3H_6, and hydrocarbons with GCVs ranging from 6.4 to 9.8MJ/kg and can be used for process heat (Akram et al., 2019).

Agricultural waste and municipal solid, the members of biomass, are considered attractive renewable energy resources with zero net carbon dioxide emissions to the atmosphere (Akram et al., 2019). Pyrolysis oil derived from agricultural wastes of GCV ranging from 15 to 38 MJ/kg has some advantages in transportation, storage, combustion, retrofitting, and flexibility in production and marketing (Joardder et al., 2014). Therefore, the cost of a heating system can be reduced by utilization of the char and gas products in the pyrolysis process.

As a result, a new solar heating concept is incorporated into the biomass heating system to offset the difficulties (Sobek and Werle, 2019). The reactor was partially heated to 162 degrees Celsius in this investigation; however, continuous heating may be more effective in reducing emissions from biomass fuel and energy costs. It is worth noting that bio-oil is derived from biomass, which is a mixture of approximately 300 types of major and minor organic compounds (i.e., acids, alcohols, ketones, aldehydes, phenols, ethers, esters, sugars, furans, nitrogen compounds, and multifunctional compounds, etc.), and has several environmental advantages over fossil fuels as a clean fuel (Lynd et al., 2015).

Furthermore, because biomass contains tiny levels of sulfur and produces more than 50% less NOx than diesel oil, bio-oil would be exempt from SOx tariffs. Furthermore, the UN Food and Agriculture Organization projected in 2005 that the top ten date producer countries generated approximately 1.67 billion tons of dates (Caputo and Maek, 2021; Joardder et al., 2014). This vast quantity of seeds is almost entirely wasted and is rarely used as feed for horses, cattle, camels, sheep, and goats (Caputo and Maek, 2021; Das et al., 2011).

As a result of its nonfood and other noncommercial uses, this trash can be employed successfully as feed material

Table 4: Properties relevant to the pyrolysis process for the primary feedstocks considered(Caputo and Mašek, 2021).

Property	Rice Husks	Sugarcane Bagasse	Corn Straw	Timber Residue	Eucalyptus Residue
Residue: Crop ratio	1:0.67	1:3.3	1:0.77	1:2.3	1:1.8
Pyrolysis Onset Temperature range (K)	473–823	473–723	473–823	498–823	483–903
Recorded Weight Loss (%)	50	65	70	75	80
Bulk Density Dry Basis (kg/m^3)	100	120	130	220	480

for energy recovery as fuel (Joardder et al., 2014). However, the high cost, complexity, and environmental risks of conventional biomass and electrical heating systems of pyrolysis technology are important hurdles (Joardder et al., 2014; K. C. Das et al., 2011). As a result, a new solar heating concept is incorporated into the biomass heating system to alleviate the concerns (Joardder et al., 2014). In this study, the innovative reactor was partially heated to 192°C using a collector; however, continuous heating may be more effective in reducing emissions from biomass fuel as well as energy costs.

Solar pyrolysis: classification and design

Solar energy has gained increasing interest in recent years as a possible sustainable energy source for pyrolysis (Caputo and Maek, 2021; Sobek and Werle, 2019). When compared to a traditional slow pyrolysis process, using solar electricity as the heat source in the reaction permits a higher proportion of the original material to be transformed into products (Figure 4). In comparison to existing approaches, it can also greatly lower pollution levels due to prevented partial combustion emissions, simplify the heating strategy, and allow faster start/up shut down sequences (Caputo and Maek, 2021). Solar pyrolysis can be divided into two categories: direct and indirect heating. The material receives heat flux primarily through radiation and conduction from the reactor walls or a heat transfer fluid in indirect feedstock heating (HTF) (Caputo and Maek, 2021). The use of an HTF, often molten salt, is very beneficial in terms of increased heat transfer rate to the materials and end-product recovery, but it requires more specialized equipment (Caputo and Maek, 2021). When appropriate extra methods to improve heat transfer rates are applied in the case of indirect feedstock heating with no HTF, performance improves dramatically (Caputo and Maek, 2021).

In the directly heated concept, the materials are heated directly via concentrated solar radiation through, at minimum, one transparent reactor surface. These kinds of systems, however, are very sensitive to the residence time of reactants in the focal zone for even pyrolysis and window cleaning requirements from tar accumulation.

One possibility is to use a cavity receiver-type aperture with a high conductivity emitter plate to transmit heat to the reactor via a larger radiative surface, as demonstrated in a solar thermochemical system for hydrogen production (Caputo and Maek, 2021; Kodama, 2003a). Because there are no direct reactions in the window-topped cavity, no sweeping gas or mechanical window cleaning equipment is required. Furthermore, when compared to a directly irradiated system, this configuration increases total internal reflections (TIR) in the cavity-type receiver, resulting in a 5% reduction in delivered flux (Caputo and Maek, 2021; Chen et al., 2014; Kodama, 2003a).

Due to the high thermal stresses normally associated with solar pyrolysis reactor operation, material compatibility is another key concern in their design (Chen et al., 2014; Kodama, 2003b). Quartz or borosilicate windows are the preferred material for indirect heating because of their transmissive ability and ability to withstand temperatures of up to 1500 K and 900 K, respectively, despite the fact that this can result in conductive and radiative heat losses of 25–43 percent (Caputo and Maek, 2021; Joardder et al., 2014; Sobek and Werle, 2019).

In addition, the insulating and inner materials must tolerate similar temperatures, wide thermal gradients, and rapid heating. To avoid undesirable secondary reactions or accidents, the internal materials must be inert to high temperature-reducing gases. Flat plate collectors are unsuitable for achieving the high heat flux and temperatures required by the pyrolysis process due to the large surface area required (Caputo and Maek, 2021; Khairnasov and Naumova, 2016; Rony et al., 2018).

CSP systems, which collect solar energy and concentrate it onto a single focal point or line, are usually the preferred technology because they have been used for high temperature solar thermochemical processing in a variety of other applications at scale, including water desalination, methane reforming, and hydrogen production (Caputo and Maek, 2021; Rony et al., 2018).

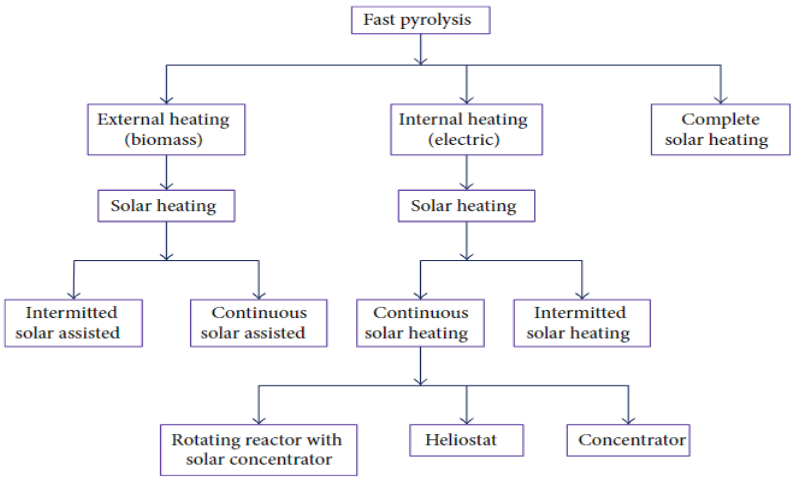

Figure 4: Classification of solar (assisted) fast Pyrolysis (Joardder et al., 2014).

The most important practical impediment to commercial-scale solar pyrolysis development has been integrating an effective CSP system. It can account for up to 60% of a solar thermal processing unit's depreciable capital. (2021, Caputo and Maek).

A solar pyrolysis process using orange peels in a tubular mono-silicate glass reactor with a 2-inch diameter mounted on the focal line of parabolic through concentrator has been more recently proposed and implemented(Caputo and Mašek, 2021). The reactor was tubular and made of quartz; however, this could only accommodate up to 1 g of the sample at the time, and thus the design is hardly scalable at the time of writing (Akram et al., 2019; Kodama, 2003a).

The reactor achieved an average temperature of 563 K, peaking at 738 K during Pyrolysis, and was able to volatize 77 percent of the original material with a 20 percent char yield by weight (Akram et al., 2019; Caputo and Maek, 2021). For the pyrolysis of scrap tire rubber at 823 K for 15 minutes, a more complicated, fully automated solar concentrator using a Fresnel Lens with 2 degrees of freedom tracking was able to achieve somewhat higher efficiencies and increased tar yields.

To obtain the requisite heat fluxes for the pyrolysis of a larger feedstock, the few examples of non-laboratory or pilot scale solutions available tend to use a central receiver system with a mirror or heliostat field. One very useful unit was recently created for the 15 kg/batch pyrolysis of jatropha seeds (Chen et al., 2014; Kodama, 2003a). To obtain a 16:1 concentration ratio onto a circular fixed bed type reactor, the unit utilized a Sheffler dish technology (Chen et al., 2014).

The batches were made without sweeping gas, and the char was collected at the end of the process through a bottom outlet. Over the course of a 15-day operation, average reactor temperatures ranged from 553 to 623 K, resulting in mean conversion rates of 80% and maximum tar and char output of 20% and 50% by weight, respectively. A 6 L Pyrex balloon was irradiated through a heliostat field and a 2 m parabolic concentrator in another recent work to pyrolyze agriculture and forestry residues at sub-atmospheric (0.52 bar) reactor conditions (Caputo and Maek, 2021; Chen et al., 2014).

Zeng et al. (2015) used a vertical axis solar furnace to wrap a beechwood sample in graphite foam. As a result, it could only be heated by conduction and convection from pyrolysis vapours, using Argon as a sweeping gas because it is transparent in the applicable wavelength area (Zeng et al., 2015).

The energy upgrade factor (EUF) for solar pyrolysis, a measure of thermochemical conversion efficiency, was determined for the first time in this study, producing 1.33 and 1.53 at 875 K and 1300 K, respectively (Zeng et al., 2015). This compares favorably to the EUF for conventional autothermal pyrolysis (EUF = 0.91) or even solar gasification (EUF = 1.18) obtained in prior research with comparable feedstocks [31,47]. EUF values greater than one indicate successful and efficient chemical energy storage, which is not typically achieved in conventional autothermal pyrolysis (Caputo and Maek, 2021; Zeng et al., 2015).

METHODOLOGY

The raw materials used as feedstock for the pyrolysis tests were sugarcane bagasse, rice husks, corn straw, wood chips, Vitex Dionna, and Gmelina Arborea seeds. The samples were correctly washed to remove any mud or foreign materials before loading into the fabricated reactor (Figures 5 and 6). It is essential to find out the various properties of the biomass. The proximate and elemental

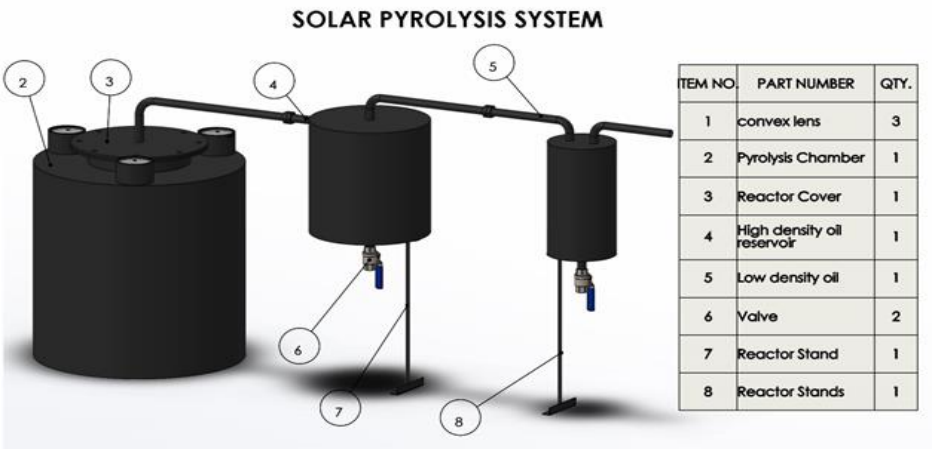

Figure 5: The Novel Solar Pyrolysis Reactor CAD Diagram.

Figure 6: Side view-photograph of the solar pyrolysis machine

analysis of one of the selected biomasses is shown in (Tables 2-3).

Fabrication: potential feedstocks and reactor sizing

The materials used include; mild steel, stainless steel, plastic, angle bars, k- type thermocouple, leather gasket, and transducer. Machine fabrication consists of various techniques such as lathe machining, drilling, boring; keyway cutting; slotting; oxyacetylene gas welding; grinding, and electric welds. The machine's schematic is shown in (Figures 5-9). Accessibility and ease of assembly were critical considerations throughout the creation of this model.

Parts are meticulously attached with care. Table 4 summarizes the key accessible potential feedstocks from agricultural and forestry waste streams in SSA (Caputo and Maek, 2021). The main construction is a steel drum with three adjustable holders, each with a Fresnel lens (Figure 5). The design was created in order to be compatible with the pyrolysis process. To begin, a portion of the top lid is removed to allow for biomass loading, and the lens is placed at an identical distance at the top of the reactor, as shown in (Figures 5-6). According to thermogravimetric analysis (TGA) from the literature (Caputo and Maek, 2021), more than 80% of these feedstocks can be degraded at temperatures below 823 K, with pyrolysis beginning temperatures around 473K.

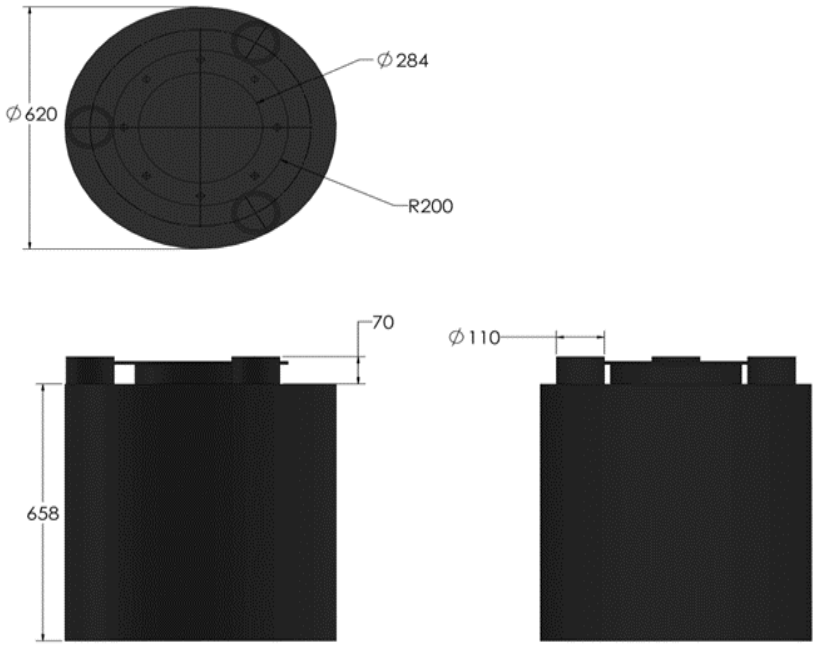

Figure 7: CAD diagram of the reactor chamber parts to be fabricated.

Because of the lower associated process energy requirements, they are appropriate products for use with a solar pyrolysis system. Furthermore, there is some evidence that greater density feedstocks have a lower residue: crop ratio. This is compatible with the establishment of a uniform unit; as equal weight amounts should be accessible from agricultural activities in the various regions under consideration.

According to SSA-wide analyses, the region's average agricultural waste generation rate is 1.5 kg/person/day (Caputo and Maek, 2021). The required volume is estimated based on the novel system to be operated by a small community of 10 people, for compatibility with the lowest feedstock density and a maximum reactor filling of 80%, to achieve sufficient heat transfer and regional agricultural waste production (Caputo and Maek, 2021).

$$V_{MinimumReactor} = \frac{1.5\frac{kg}{person * day} \times 10\frac{people}{reactor}}{\left(100\frac{kg}{m^3}\right) \times (80\%\, max filling)} = 0.1875\ \mathrm{m}^3 \quad (1)$$

The most frequent drum size is found to be the closest match: (200 L) cylindrical stainless-steel drum insulated with bricks to prevent thermal losses. The prefabricated container is considered an excellent solution since it has a very similar volume to the estimated required one while also possessing powerful anti-corrosive and thermal features (Caputo and Maek, 2021). A similar approach is used to size various tubing and valve components, which are sized using accessible water pipe specifications to reduce the need for specialized component production.

Pyrolysis heat transfer approach

Previously published empirical correlations for optimal aperture size through reactor target temperature were used to construct a receiver set-up (Caputo and Maek, 2021; Chen et al., 2014; Khairnasov and Naumova, 2016; Kodama, 2003b; Rony et al., 2018). The three lenses were positioned to collect heat from the sun and then onto a combustible fiber to allow radiative heat transfer from the solar unit at the reactor's top to the stainless steel pyrolysis chamber (Figures 5 and 6). Because of the limited feedstock pre-treatment and the need for simplicity, batch reactor mixing was not adopted. Instead, two sets of heat pipes were installed, one for the inlet and one for the outflow of the pyrolysis products. To begin, an anti-gravity loop heat pipe at the reactor's center was constructed to help transmit radiative energy from the pyrolysis chamber into the feedstock's central and lower parts.

Vertical capillary heat pipes supplement this by uniformly distributing the power from the onsite gas combustion into the reactor's bottom half. This decision was driven by the unit's probable feedstock particle density and void ratio. They minimize the advantages of a mixing system while raising the necessity for an appropriate heat transfer mechanism (Caputo and Maek, 2021; Sharma et al., 2015).

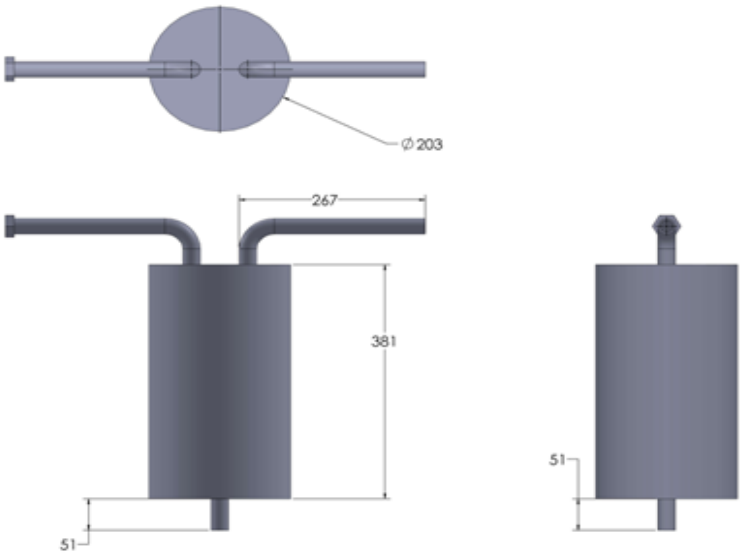

Figure 8: CAD diagram of the low-density oil reservoir.

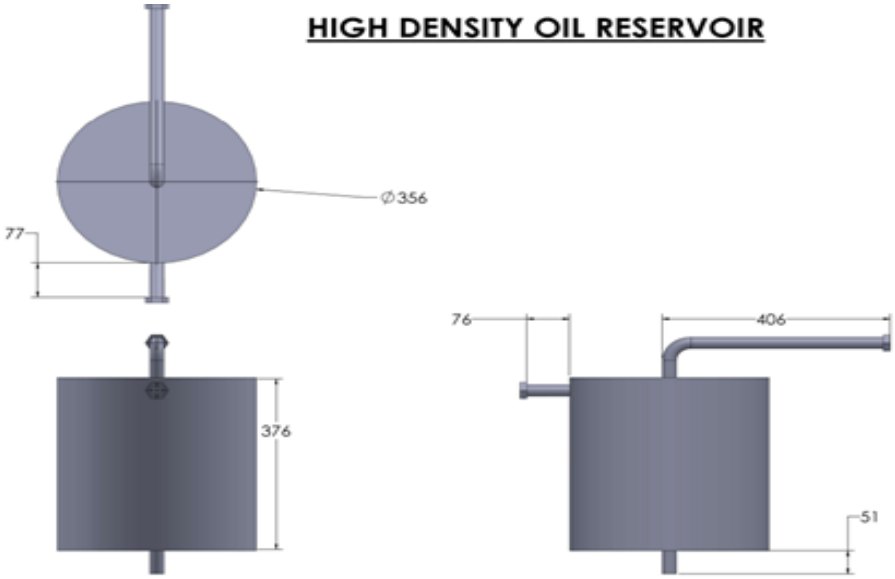

Figure 9: The CAD diagram of the high-density oil reservoir.

To guarantee proper heat dispersion, the inner chamber was lined with bricks. Insulation is also necessary to supplement the heat transfer strategy by reducing energy losses. However, a lower limit of 1.1 MJ/kg is applied for the computations here (Caputo and Maek, 2021; Jadhav and Venkatraj, 2018; Zeng et al., 2015).

$$Qmin_{combustion\ chamber} = 1.1\frac{MJ}{kg} \times 0.001864\frac{m^3}{s} \times 0.960\frac{kg}{m^3} \times 25\%\,\text{efficiency} = 492W \quad (2)$$

The heat balance of the system is generally

Figure 10: Brick lining as insulator of the reactor chamber.

(Caputo and Maek, 2021) estimated

$$Q_{solar} = Q_{reactor} + Q_{biomass} + Q_{reactions} + Q_{loss} \quad (3)$$

Where $Q_{reactor}$ is composed of the energy to heat both the reactor wall and the lens place configuration, $Q_{biomass}$ includes both the power for moisture evaporation to bring the biomass material up to the desired pyrolysis temperature. At the same time, $Q_{reactions}$ are the heat needed to meet the activation energy to decompose the primary biomass pseudo components. Q_{loss} is instead the energy lost to the environment through combined conduction, radiation, and convection phenomena, which is calculated as(Caputo and Mašek, 2021):

$$Q_{loss} = Q_{optical\ losses} + \sum_{i=0}^{N}[Q^i_{conduction} + Q^i_{convection} + Q^i_{radiation}] \quad (4)$$

Where $Q_{optical}$ losses are the sum of energy losses from the slope surface errors and nonperfect reflectivity of the low-cost CSP materials, and i represents each heat transfer surface, simplified for analysis as the receiver aperture plus cavity walls, reactor side walls, insulation, and combustion chamber. Heat losses from other surfaces are thus assumed to be negligible compared to the total system energy flux. The conduction losses are then calculated for each character as:

$$Q_{conduction\ loss}{}^{i} = (k_i/t_i)A_i(T_i - T_{env}) = h_{cond,i}(T_i - T_{env}) \quad (5)$$

where k is the thermal conductivity (W/m K), ti is the thickness of the conduction medium, Ai is the surface area, hcond,i is the conductive heat transfer coefficient (W/m2 K), and (Ti - Tenv) is the temperature difference in K between the reference surface I and the outside environment. According to (Jadhav and Venkatraj, 2018; Shuai et al., 2008), the radiative losses are as follows:

$$Q_{radiation\ loss}{}^{i} = \varepsilon_i\, \sigma\left(T_i^4 - T_{env}^4\right)A_i \quad (6)$$

Where "ϵ_i is the emissivity of surface i, σ is the Stefan Boltzmann constant (5.67 x 10^{-8} W/m^2 K^4), and A_i is the radiative surface area. Radiation losses from the bottom wall of the reactor are assumed to be negligible as a very minimal temperature difference will be present there until the combustion chamber starts running. At this point, the chamber is expected to experience higher temperatures than the reactor.

RESULTS AND DISCUSSION

Solar Unit

The heating source was selected after the reactor geometry had been determined. Three Fresnel lenses were used to collect radiative heat from the sun into the

heating chamber. The resulting solar pyrolysis unit consists of three primary collectors made of a convex lens mounted on the reactor chamber. Bricks were used in lining the chamber walls, and a stainless-steel pyrolysis reactor was sandwiched between the lining and the outer wall of the mild steel reactor. This allows them to be separated at the end of the process for easier reactor maintenance and simplifies the collection of any leftover solid residue at the bottom of the reactor (Figures 6 and 10). The final configuration for the novel solar pyrolysis system is shown in (Figure 6).

Biomass Feedstock

Based on this initial testing, the reactor should achieve the near-complete pyrolysis of all potential feedstocks presented, albeit the time estimated for some exceeds the 2-h residence time targeted. Higher density feedstocks seem to produce better performance, although a more detailed heat transfer model would help clarify this. The targeted char production means more room for error in the pyrolysis process. There is no reason to inhibit secondary tar cracking reactions, given it is not collected. Therefore, the reactor could be allowed to run for longer than two h if needed, as even if no more manual tracking adjustments are made to minimize the impact on the farmers' routine. Lower density agricultural residues are pyrolysed more efficiently; however, they are limited by the same property on their max char production potential and net product energy content. They present lower biomass HHV, to begin with, than woody residues.

Nonetheless, agricultural residues are expected to be much more readily available based on the implementation in rural farming communities and the crop–residue ratios. Thus, reactor compatibility with them is more critical to its sustainable and practical performance. There is potential to further investigate-cost efficient mechanisms for the unit to allow more granular temperature control over the process, achieve higher operating heat fluxes, and optimize conditions based on feedstock composition.

Control/Instrumentation Box

A solar-powered battery pack system is used to instrument the novel pyrolysis system. A temperature sensor is used to determine the temperature of the reactor. Based on the feedstock availability and the local output demand, it could also be deemed appropriate to use the reactor for more than 1 batch per day and the sensor taking the temperature per unit time. Depending on the extent of this decision, the unit's lifetime may be significantly reduced as low-cost materials were the preferred choice for many components. Nonetheless, all selected materials present good resistance to corrosivity and thermal shocks expected from the operation and thus, with minimal maintenance, should be able to allow long-term operation.

Environmental and social impact

The environmental and social impacts of the project are numerous, and overall, the system is expected to perform exceptionally well in both metrics. The positive environmental impact of a pyrolysis system comes from the combined effect of a reduction in kerosene used for lighting, diesel used for electricity generation, and an increase in highly stable carbon stored in the soil from biochar application reducing the need for chemical fertilizers.

The utilization of solar power as the energy source boosts the system's sustainability by lowering emissions caused by car thermal combustion. The reduction of organic materials left to degrade in the open or burned on agriculture, both of which contribute significantly to GHG emissions, provides major environmental benefits for the region (Caputo and Maek, 2021). This is especially important given the lack of a solid waste management plan in most SSA, which results in a significant number of landfills and inappropriately dumped waste (Caputo and Maek, 2021). A considerable amount of this trash is also constituted of plastic, which degrades soil qualities and contaminates the already scarce water supply, which has previously been effectively pyrolyzed in conjunction with agricultural leftovers.

Conclusion

While designing a pilot-scale pyrolysis machine, the energy calculations were needed as a baseline to decide how this machine would operate and if it was feasible. The advantages of a continuous pyrolysis process in terms of the ability to control outputs and optimize yields remain and should be investigated further in future iterations of the project. A potential implementation pathway would be through a community-based pyrolysis unit, with operators rotating and feedstock collection among the various community members. This kind of novel reactor could allow for more electricity and energy by-product production; which as rural communities continue moving up the energy ladder will become increasingly important. However, such a large-scale system would have to be designed for more specific kinds of feedstocks and operating conditions to internalize the benefits of a more complex control unit.

The design and testing performed as part of this paper have provided an essential step toward deploying such novel solar pyrolysis units for application in rural communities in SSA. The design process employed seems to have yielded an overall efficient system, particularly considering the cost minimization approach implemented, which should be able to achieve the

pyrolysis of a broad range of biomass residues while enhancing sustainable development. The novel solar reactor is also elementary to operate with minimal moving parts and labour requirements, which is likely to increase acceptance by local populations. However, many uncertainties remain on how the system will perform in the field, which is essential to address in future work. The most crucial consideration in addressing these uncertainties regarding the overall feasibility of the system is the actual yield, composition, and resulting soil amendment value of biochar, as it is a significant determinant of the added benefits produced by the unit. There is an abundance of studies on this topic, however, and thus.

At the same time, no experimental data about our specific unit; reasonable assumptions aligned with the literature were made for feasibility assessment purposes. The actual optical efficiency of the system at different locations and times of the year also ought to be investigated further in the future, as the values presented for the representative site were merely intended as a proof of concept.

Authors' contributions

Conceptualization of design, Suleiman I.A; Methodology, Suleiman I.A.; Testing and assessment Suleiman I.A., Oregbeme Henry; Writing original draft Suleiman I.A; Review and editing Suleiman I.A.

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