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Design and Development of a Pyrolysis Reactor to Produce Biochar at Industrial Scale

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Abstract: A pyrolysis reactor, operating at medium pyrolysis conditions (at 550 ^{0}C temperature and 2 hrs of residence time) to continuously produce biochar was developed. The interruption caused by routine loading and unloading is eliminated by a screw mechanism that allows mechanized loading and unloading. Biochar as a bio fertilizer could be well matched with the current Sri Lankan agro community's expectations on conserving the soil and its quality. The proposed design is capable of producing biochar at a rate of 100 g/min. A scaled-down 10 g/min prototype was built to measure and validate required temperature levels, continuous production, and the complete conversion of the biomass into biochar. Readily available cinnamon sticks and corncobs were utilized as biomass to create separate biochar samples. The biochar yields were measured as approximately 32% for cinnamon and 28% for corncobs. Further testing of biochar samples for their structural morphology displayed a significant number of pores ranging from micro to macro scale (good porosity). These porous morphologies would enable capturing diffusive substance and trap them, while acting as mass transfer channels. Due to these unique qualities, biochar can act as an effective fertilizer for soil, facilitating fast adsorption, retention, and slow diffusion of nutrient agents. So, this could well fit in to serve the purpose of using this product as a biofertilizer to remedy the loss of soil fertility due to the extensive use of chemical fertilizers.

Keywords: Biochar, Cinnamon, Corncobs, Design, Pyrolysis, Reactor, Soil Sustainability,

1. Introduction

A fertile soil as we call it, enriched with proper levels of nutrients, other inorganic particles, organic matter, water, and air, has been the strength of the Sri Lankan agro community for years. Plant growth takes nutrients from the soil and the balance is maintained by returning them back to the soil as residual biomass which is known to us as the nutrient cycle. To cater for the demand of the growing population, the soil is being utilized more extensively for agriculture, ultimately risking the compromised balance of the nutrient cycle. Moreover, this expedited production indeed has been rigged with numerous misconducts which directly and indirectly put the fertility of the soil in serious peril. Extensive use of chemical fertilizers as one of such misconducts has reasonably recognized to be the cause for the accumulation of insoluble forms of contaminants inside the soil that could ultimately cause the depletion of soil fertility as well as the quality. These adverse effects are caused by the hinderance of proper nutrient adsorption in the soil. Efforts to eliminate aforementioned malpractices are driving the industry into a paradigm shift with the influence of sustainable development, while food security has also emerged as an hourly need.

Most conventional agricultural practices in Sri Lanka are rigged with numerous misconducts with the immediate short-term focus on satisfying the demand, and the subsequent effects of these malpractices have led to many disadvantages. Whether malpractice originated from bad policies, mismanagement, or any other reason, it could propagate and adversely affect social, health and, environmental aspects alike. In this particular context, it is imperative to adopt sustainable countermeasures to reverse at least some of the damage caused by past mistakes.

1.1 Chemical Fertilizers and Soil Degradation

Sri Lanka is a highly fertile landscape which opens up a vast spectrum of possibilities for the agricultural sector. In the first quarter of 2018,

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agriculture has contributed to 7% of country's GDP [1]. Five decades ago, in 1950, this contribution was remarkably high around 41% [2]. Thus, it is clear that the growth of the agricultural industry has been hindered and degrading for decades. The hesitation for improvisation has left the country, what could have been an agricultural behemoth, in a futile position. One of the most noticeable agricultural malpractices seen in Sri Lanka is the uncontrolled and excessive use of chemicals throughout agricultural processes. Residues of chemical pesticides and fertilizers could accumulate in solid, water, air, and even in human bodies through agricultural products. This can lead to countless hazardous scenarios in the long run [3]. This particular research project addresses the soil degradation scenario in Sri Lanka, and aims to provide a sophisticated, industrial scale solution to counter the cumulative damage and possibly reduce the sub-standard chemical usage in the agriculture industry. In Sri Lankan agriculture policy draft published in 2019, low productivity due to land degradation and poor land management has been identified as a major weakness in existing agricultural structure. This would further emphasize the significance of the matter in hand, highlighting the importance of minimizing agro-chemical pesticides and replacing them with eco-friendly practices [4]. It is believed that the final outcome of the project, an industrial level reactor to produce biochar, would compensate for the negative consequences of absence of an up-to-date soil conservation act in Sri Lanka [5].

Among many biotic and abiotic factors that affect crop growth and productivity, soil quality is considered to be one of the most important. Plants require a number of elements from soil as macronutrients (Nitrogen, Phosphorus), and micronutrients (Boron, Iron) for their growth [6]. Soil nutrient levels may decrease over time after crop harvesting, as nutrients are not returned to the soil [7]. In order to keep the agricultural cycle intact, chemical fertilizers have been the choice to gain the required nutrients in the soil. But, only a small amount of nutrients is absorbed by the plants and rest is left in the soil itself. Even though most of these chemical fertilizers are soluble in water, they are gradually converted into insoluble forms when left unused. Also, such chemical residues could run down into nearby water bodies, causing eutrophication [8]. Cumulative effect of extreme use of pesticides, fertilizers, and other chemicals (inorganic fertilizers) could degrade the soil quality of a fertile land, as well as water sources, ultimately resulting in a low yielding cropping system [9].

On the other hand, bio fertilizers (organic fertilizers), can reenergize the soil by improving the soil fertility and hence can be used as a powerful tool for sustainable agriculture, rendering agro-ecosystems stress-free. Mass adoption of organic fertilizers in place of inorganic fertilizers can be further justified by their relatively low cost, and effective utilization of municipal waste what otherwise could have ended up in landfills or incineration sites. Biochar is a mainstream, sustainable, organic alternative that can be used to enrich and improve degraded soils.

1.2 Roll of Biochar as a Soil Amendment

Carbon rich biochar is desirable among other organic soil amendments because it can be easily derived from readily available biomass sources. Wood, manure, leaves, and even human sewage can be reduced into biomass under a controlled pyrolysis process [10]. In the pyrolysis process, biomass is thermally decomposed with little to no Oxygen, in relatively low temperatures. The process closely resembles the charcoal production process, but with the final outcome being solely focused on agricultural applications [11]. During the pyrolysis, carbon-based feedstock is converted into highly black biochar with high porosities and pH values. Due to its porous structure, biochar is lightweight and possesses a large external surface area. These pores could accommodate nutrients and friendly microorganisms that are necessary for optimal plant growth, preventing them from casting away from adverse environmental conditions (rainwater, heavy winds). A paper published in 2011 states that, application of biochar has a direct effect on soil biota, as the population of microorganisms is significantly improved by it [12]. Aside from the major fraction of carbon, biochar consists of nitrogen, sulfur, oxygen and hydrogen [13]. These inherent properties of biochar particularly come in handy when conditioning damaged soil in agricultural areas. Combined application of friendly soil organisms, some fraction of forest soil and biochar on a land would increase the crop yield as much as 300% [14]. Quality and the quantity of biochar reduced from a fixed amount of biomass is largely dependent on the pyrolysis parameters [15]. Also, its effects vary with different types of biomasses used, soil conditions, and amounts applied. By optimizing the efficiency of pyrolyzing reaction which derives biochar from biomasses, not only the quality will improve, but also significant economic margins would be achieved for low-income communities of farmers.

The main objective of the project is designing and developing an industrial scale biochar production reactor optimized through CFD analyses. At the end, as the project outcome, a full-scale biochar reactor was designed and optimized through the Ansys fluent simulation package. Subsequently, a scaled down model of the reactor was fabricated with a 10 g/min bio-char production rate whereas the full-scale reactor is capable of 100 g/min production rate.

2. Background

2.1 State-of-the-Art

Pyrolysis under 400–800 °C put organic feed stocks under a biochemical conversion, resulting in charred matters (Equation 1). During the pyrolysis process, some parts of the organic feedstock are transformed into liquid (either tar or oil based on the pyrolysis conditions). Syngas is a mixture of gases produced by the gasification of biomass, which is a thermochemical reaction that converts organic material gases (typically carbon monoxide (CO), hydrogen (H_2), etc.).

$$\begin{matrix}\text{Biomass}\\ \text{(Solid)}\end{matrix} \longrightarrow \text{Biochar} + \begin{matrix}\text{Liquid}\\ \text{(tar) or oil}\end{matrix} + \text{Syngas} \ldots (1)$$

Depending on the operating temperature, pyrolysis processes are classified as slow and fast (Figure 1). Fast pyrolysis (usually with >500 °C) temperatures emphasizes the production of bio-oils over biochar and slow pyrolysis (with 250-500 °C temperatures) highlights biochar production over bio-oils. As the name suggests, slow pyrolysis takes a considerable amount of time (around 30 min to few hrs) to complete.

Aside from the pyrolysis, gasification and Torrefaction methods are also used to produce biochar, but they could be either slow or demand higher temperatures in contrast [16]. Thus, pyrolysis was chosen as the most optimal mechanism to be utilized in the intended reactor. Among the two main factors which control the quality of produces biochar, state of the pyrolysis reaction and the state of feedstock, the former should be paid more attention when manufacturing the intended reactor.

Biochar can be manufactured in both domestic and industrial scales. Domestic manufacturing processes are executed through small scale stoves or kilns. Numerous researches are available of developing these micro stoves, with the focus on reduction of indoor air pollution, providing alternative income source for low income families, and enhancing the sustainability of small-scale agricultural practices. As an example, the micro gasifier

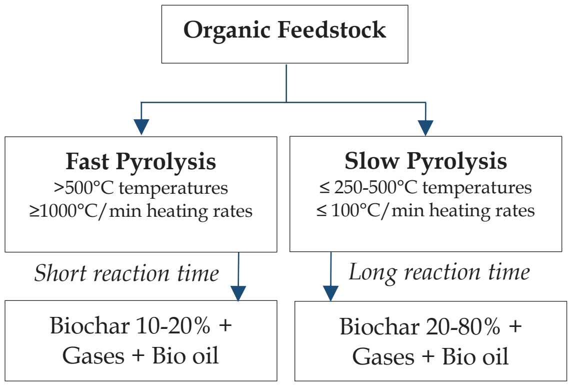


Figure 1 - Classification of Pyrolysis Processes Used in Biochar Production

proposed by Birzer et al. [17] was able to utilize the top-lit up-draft mechanism to produce biochar with cow dung. The research was mainly focused on humanitarian aspects, allowing low-income households to sell the byproduct (biochar) of daily cooking activities and generate an alternative income stream. When it comes to the industrial level biochar production, the discussion of coproducing biochar and bio-oil is trending. Subsequent results of multiple studies that extensively focused on bio-oil can be provided. The studies have proved that, with higher pyrolysis temperatures and small particle sizes of feedstock, the biochar yield has decreased. Also, it was suggested that a particular kiln/ stove can be optimized to either produce more biochar or more bio-oil by controlling the pyrolysis temperatures [18, 19]. Even though recovering bio-oil would increase the efficiency of the process significantly, the intended reactor was decided to be optimized for biochar production. This research is meant to be the preliminary step into the industrial biochar production in Sri Lanka, and overcomplicating the design seemed suboptimal at the time.

As for the literature on high-capacity industrial biochar production, several types of production systems were pinpointed. Between them, an optimal type was to be chosen prior to progress into the design stage. The traditional earth mounds or pit kilns can be identified as the most primitive kind of production systems for biochar. They are able to produce quality biochar but at low yield efficiencies. The retort type kilns, which allow the pyrolysis gases to circulate back and internally provide additional fuel to the reaction, have also been discussed extensively. The kilns would have an increased capacity over non-retort kilns, as well as comparatively less mission. But the higher investment costs associated with retort type kilns seem not to justify the decision of replacing non-retort kilns, especially when low-cost margins are associated [20]. A study conducted in 2015 suggests that, instead of making the pyrolysis chamber completely airtight, a semi-airtight arrangement that allows to take the sin gas out and combust at a later stage externally would increase the production efficiency significantly [21]. Thus, the same strategy was decided to be integrated into the intended design by facilitating clearance that allows biogas to escape and heat up the external surface of the pyrolysis chamber. The modern and highly technical method of microwave pyrolysis is known to produce uniform, high-quality biochar in fast phase but it was also omitted from the decision-making process due to the high capital and operating costs involved [22]. The flame curtain method is another scientifically optimized method of biochar production gaining popularity in the recent era. The method involves pyrolyzing the feedstock stack up, layer by layer, in a conically formed chamber, either as a pit or a metal structure. Cornelissen et al. [23] claim that the flame curtain "Kon-Tiki" could produce biochar complying with international standards, with very low emissions. Also, they can be used by both large- and small-scale manufacturers due to their low operating costs. Auger pyrolysis technique is yet another promising method of biochar production. The simplicity of operation and mobility can be identified as the noticeable qualities of auger pyrolysis method. Also, the operator would have good control over pyrolysis parameters because of its arrangement [24]. Combining that with the possibility of auger mechanism to be automated at a low cost in later development stages, it was finalized to be used in the prospective design over the fire curtain method.

2.2 Auger Pyrolysis Technique

The most remarkable characteristic of the auger method is the single or twin screws used to feed biomass in a continuous manner. While rotating, the enclosed screw could move the feedstock forward through the pyrolysis chamber. The screw enclosure itself is working as the pyrolysis chamber. The rotational speed of the screw could manipulate the biomass feeding rate. Temperature of the reaction must be chosen accordingly, such that all complete pyrolysis is achieved while biomass reaches the end of the screw.

The screw arrangement can either be vertical or horizontal. At a glance, the vertical auger system proposed by Brassard et al. [25] seemed to be needing more components and consequently higher capital than the horizontal auger system proposed by Laird et al. [26] thus the horizontal option [27] was chosen for the intended design (Figure 2). The concern of small particles getting stuck between screw threads and the enclosure also affected the decision. The bio-oil yield of auger reactors which depends on the pyrolysis conditions entraps inside the screw enclosure could trigger secondary reactions, ultimately increasing the char yield at the expense of oil yield. However, openings must be facilitated throughout the enclosure to allow the secondary reaction gases to escape.

The biochar making process inside an auger reactor, and inside other kind of reactors too for that matter, can be fractioned into 4 steps, namely, (1) Moisture evaporation process; (2) De gasification processes; (3) Carbonization process; and (4) Cooling process. Prior to these steps, biomass is first stored inside the feeder. In the feeder, with the aid of hot and dry air coming from the reactor, biomass is pre-dried and pre-heated. With the controlled rotation of the feeding screw, biomass then travels forward while progressively undergoing pyrolysis. At the end of the screw, fully developed biochar is collected.

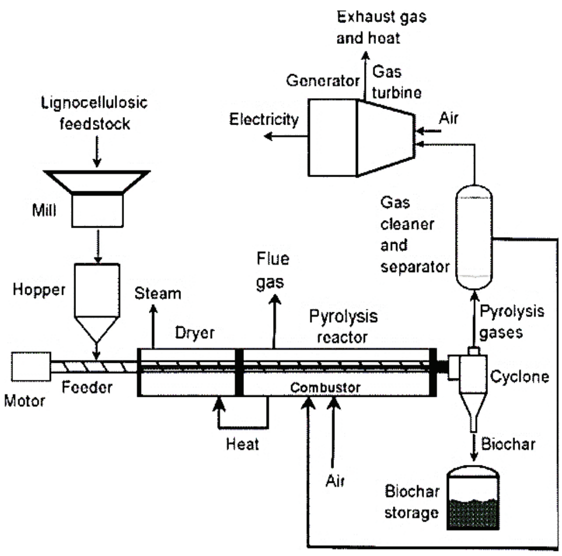


Figure 2 - Schematic Diagram of the Horizontal Auger Bio-Oil and Biochar Producing Kiln with a Drying Section as Proposed by Laird et al. (2009)

3 Design and Development

3.1 Calculations for Dimensions

Before proceeding to the design stage, it was decided to estimate the basic overall dimensions of the kiln. The targeted biochar production rate was set to a minimum of 100 g/min. Calculations were carried out based on a few assumptions.

- Mass fraction of biochar yield is 33% by weight (with respect to the input mass of biomass)
- Corncobs and cinnamon sticks will be used as the biomass and they are fed into the kiln as 1 × 1 × 1 (inch × inch × inch) cubes.

The feeding rate of biomass was calculated through the yield rate. Corncobs and cinnamon sticks will be used as the biomass and they are fed into the kiln as 1 ✕ 1 ✕ 1 (inch ✕ inch ✕ inch) cubes. The feeding rate of biomass (FRBM) was calculated through the yield rate.

$$FRBM = \frac{100}{0.33} = 303.03 \text{ g} \quad \cdots (2)$$

With a safety margin, the feeding rate was rounded up to 330 g/min. For same 330 g weight, cinnamon sticks occupied 1100 cm^3, and corncobs occupied roughly 3500 cm^3 bulk volumes. The calculations were progressed with the greater bulk volume of 3500 cm^3. Screw length and pitch were assumed as 1.6 m and 120 mm, respectively. For 2 hrs of travel time, travel speed (TV) and rotational speed (RV),

$$TV = \frac{1.6\, m}{7200\, s} = 2.22 \times 10^{-4}\ ms^{-1} \quad \cdots (3)$$

$$RV = \frac{60 \times TV}{Pitch} = 0.111\, rpm \quad \cdots (4)$$

In order to achieve the 0.111 rpm from already available resources, a motor of 1 hp (~ 1000 rpm) was used and reduced through two 30:1 gear boxes and a belt and pulley arrangement. According to the calculation method extracted from Wable and Kurkute [28], screw shaft diameter as 50 mm and screw outer diameter as 585 mm were evaluated.

3.2 Designing of the Pyrolysis Reactor

Dassault SolidWorks software was used for the design. The main reason to use this software was the offered parametric design architecture and convenience of assembling the whole system after designing the subcomponents. The main component of the whole kiln, the reactor, was first taken into consideration. The enclosure that accommodates the screw was decided to be developed as a cylindrical one which encloses the whole screw, while allowing some space at the top to collect by produced syngas. While inner chamber was enclosing the screw, outer chamber was to be fabricated around it, allowing some space in between two chambers. The main purpose of adding that intermediate space was to collect the syngas generated from the pyrolysis process. However, since the outer chamber will be the one that comes in direct contact with fire, this space was thought to be kept as small as possible in order to make sure maximum amount of heat is transferred into the inner chamber. Additionally, the bottom half of the space was to be filled with a conductive material leaving enough space in the top half for syngas. To feed the biomass, an inclined chute was included. 6 mm thickness mild steel plates were decided for the fabrication, with the expectation of upgrading into 10 mm plates as the budget allows. The weight and strength of the kiln base were also to be taken into account. Since the generation of syngas would be increased along the screw length, the intermediate space was to be made more spacious by inclining the outer chamber by a little in the clockwise direction (Figure 3). The simple idea was to keep the reactor on top of a furnace and heat it from the bottom. But due to some problems related to significant heat loss to the environment which were presumed at a later stage, it was decided to modify the initial design. Through the modification, the outer reactor wall was expanded as a brick wall arched around the internal enclosure that could also enclose the furnace. It was assumed that heat waves coming from the bottom would get reflected by the enlarged outer wall, resulting in a more homogeneous heat distribution in all directions. Considering the low bulk density of the pre-heated biomass, the inclination was increased to 45^0 from the initially decided value 15^0 to ensure the free flow of biomass to the feeder without any interruption.

Instead of preheating the biomass through the first half of feeding screw, preheating it in the chute seemed to be a possibility after the modification. With the expanded outer chamber, some length of the feeding pipe was included

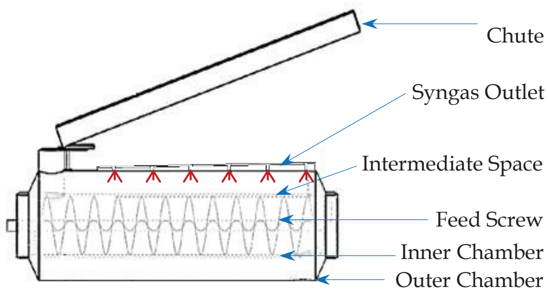


Figure 3 - Initial Design of the Reactor

inside it. So, the preheating would be aided by the heated air flow accumulated at the top of the outer chamber, waiting to be exhausted. To further heat up the top surface of the inner reactor, syngas was set to combust immediately after it came out of the outlet. The temperature was to be controlled by supplying the fuel when necessary and through primary and secondary air supply systems. A grate system was integrated at the bottom in order to make the ash removal process automated to some extent.

Just above the grate system, a biomass fuel input door was included. Due to the increased cost, including additional screws and pneumatic or hydraulic equipment to fully automate the ash removal process was not considered for this design. The potential problems that could arise by ash deposition, such as interruptions to the primary air flow, were thoroughly considered when designing the grate system. An illustration of the final design is shown in Figure 4.

3.3 Validation of the Design

The Ansys Fluent version 16.0 software was used to validate the final design of the reactor using Computational Fluid Dynamics (CFD) principles. According to the results evaluated from the simulation, the design was to be further optimized. At the initial stage of the simulation, the effect of heat generated at the expense of syngas was neglected and primary heat source of biomass fuel (fed from the bottom, not the biomass that is meant to undergo pyrolysis inside the internal chamber) was set up as a steady state heat generating source. Since the main purpose of the simulation was to validate the developed design and optimize it further, the simulation was kept to simple standards. Once the prototype is ready for experimental testing and data gathering, the simulation shall be more refined. There, instead of a steady heat generation source, a sophisticated biomass combustion model should represent the heat input along with the added effect of the heat generated through syngas combustion of the top. The simulation model was to be validated through equalizing the result from a similar simulation. Hence, as the benchmark, a previous simulation of a top-lit-up-draft biochar stove designed by Liyanage et al. [29] was used (Figure 5). After equalizing the simulation results of temperature distribution within a 95% error margin, the simulation model was assigned to the current pyrolysis reactor design. Initial simulation (Figure 6 (a)) showed a major flaw in the original design. A significant fraction of the heated-up air flow seemed to be leaking back through the air inlet opening. In order for the kiln to operate at its maximum efficiency, the heated-up airflow is supposed to fully reach the internal chamber through natural draft and power the pyrolysis reaction. In order to counter the problem, it was decided to increase the internal diameter of the exhaust pipe from 50 mm to 100 mm (Figure 6(b)). After the modification, the problem was resolved to a greater extent.

Figure 7 illustrates the temperature distribution inside the kiln as a contour plot of middle slice plane. The distribution of temperature along the height is graphically represented along with.

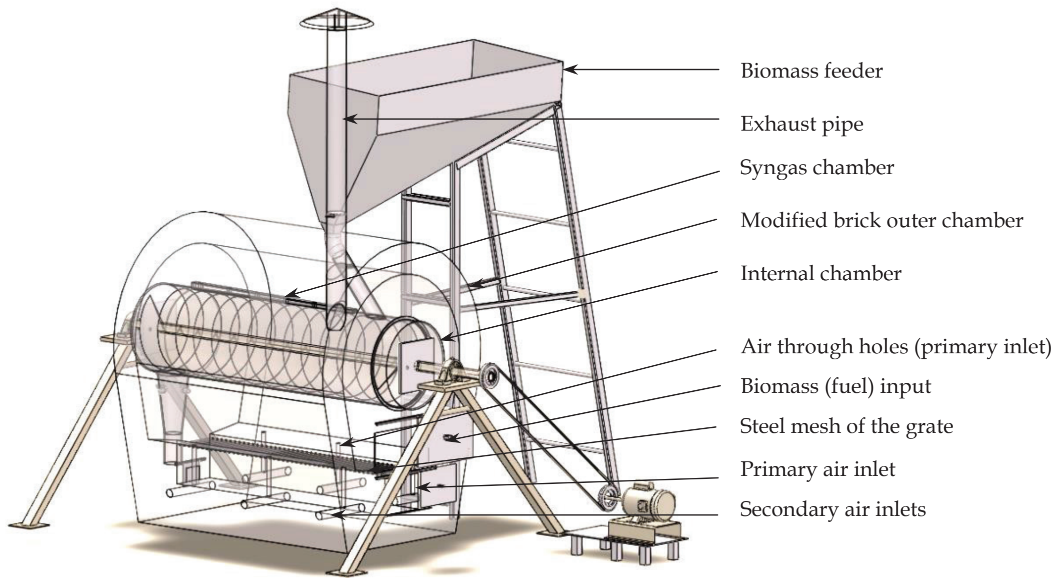


Figure 4 - Final Design of the Biochar Pyrolysis Reactor with All the Components Included

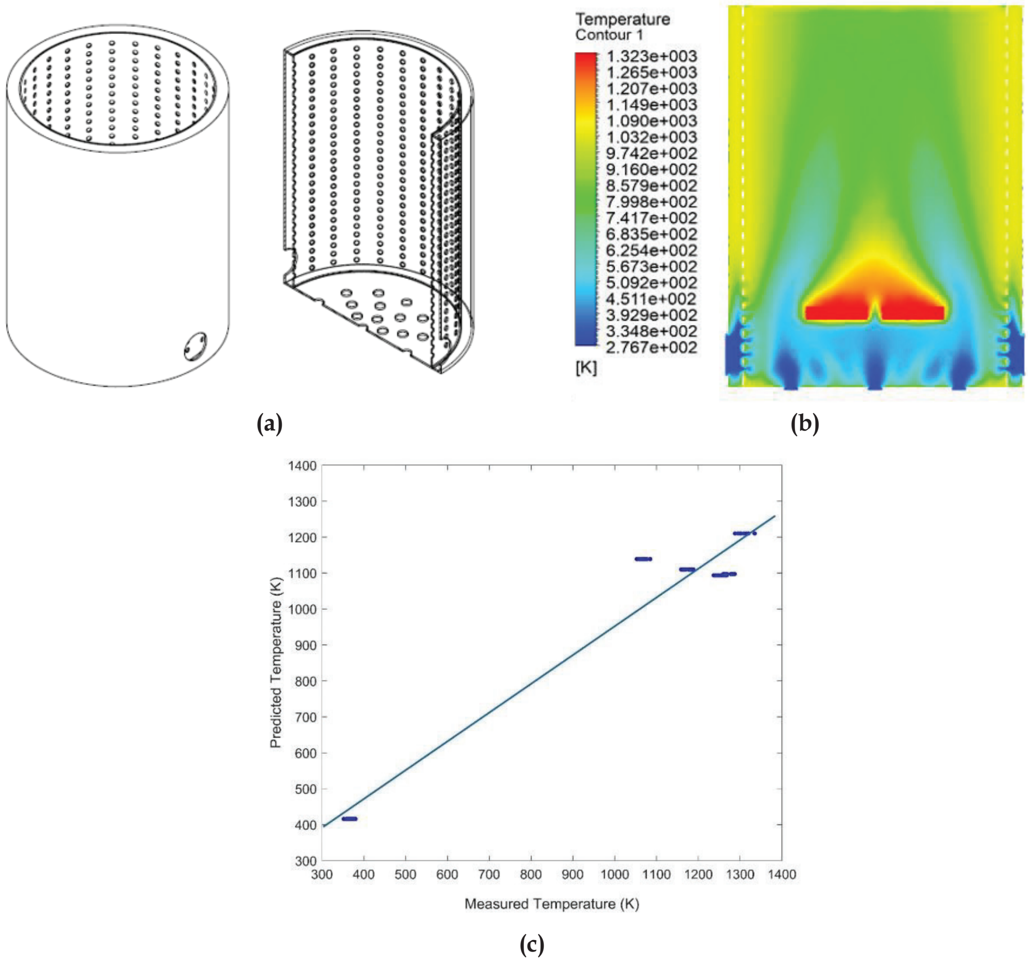


Figure 5 - Validation of the Simulation Model, (a) Cook Stove Design Used in the Validation, (b) Contour Plot of Temperature Distribution Inside the Cook Stove and, (c) 95% Correlation Line between Simulation (Predicted) Results and Experimental (Measured) Results

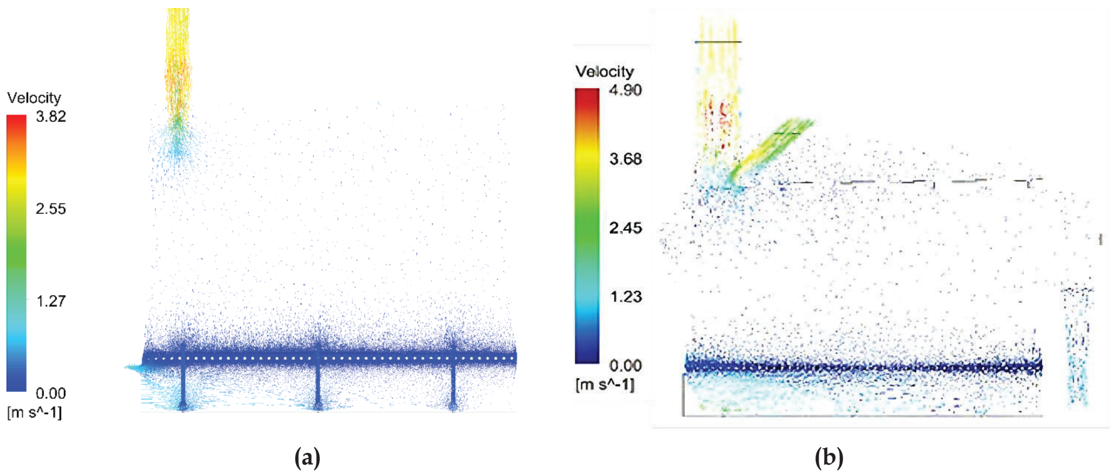


Figure 6 - (a) Leaking of Air through the Air Inlet in Original Design, as Simulated, and (b) Leakage Reduced to a Negligible Level after the Modification

The contour plot was extracted from the simulation after letting the system some time (5 mins) to reach steady state. A constant heat source of 800 ^{0}C was assigned just above the grate plane. The temperature value of 800 ^{0}C was chosen to fairly represent a controlled air flow wood combustion. Both air supply through primary and secondary outlets, and the air flow inside the outer chamber were set as natural drafts. The heat distribution will be dictated by both natural convection of the air flow as well as the radiation. The internal chamber was represented by a thin-walled cylinder in the simulation setup (seen as a rectangle on the planer contour plot (Figure 7). It is clear from the contour plot that the outer surface of internal chamber heats up to about 500 ^{0}C temperature. Thus, it was proven that proposed design is capable of executing the pyrolysis process (at around 350 ^{0}C - 500 ^{0}C) inside the inner chamber. The design was then finalized.

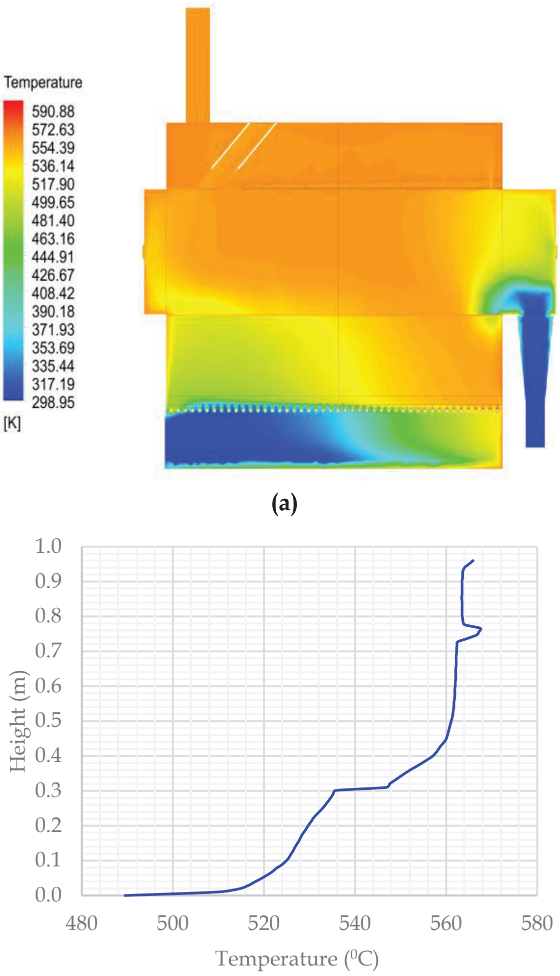


Figure 7 - (a) Contour Plot of Temperature Distribution Inside the Kiln (Near the Internal Chamber Outer Surface is Getting Around 450 ^{0}C - 500 ^{0}C Temperature), and (b) Plot of Temperature Distribution with Respect to the Height

3.4 Fabrication of Prototype

It is to be noted that the prototype fabricated was a scaled down version of the main design. Facilitating the convenience of measuring temperature profiles, feed rates, air flows and reducing the fabrication budget were the main reasons which led to the decision. A comparison of major dimensions and operational parameters between the original design and prototype are given in Table 1. The specifications for the model were set based on multiple extensive surveys conducted with prospective end users.

Table 1 - Comparison of Dimensions and Operational Parameters between the Prototype and Model

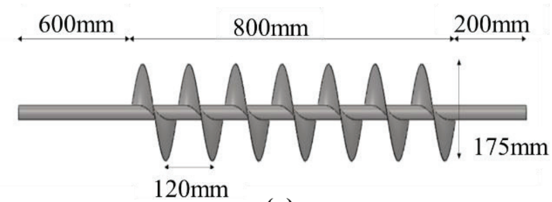
Operational parameter/ dimension	Prototype	Original design
Screw diameter (Outer)	175 mm	585 mm
Screw pitch	120 mm	120 mm
Screw length	800 mm	1600 mm
Screw shaft diameter	25.4 mm	50 mm
Biochar production rate (for Corncobs)	10 g/min	100 g/min
Residence time	2 hrs	2 hrs
Operating time	8 hrs/day	8 hrs/day

The residence time of biomass inside the screw was a necessary factor for pyrolysis process, thus the short screw had to be rotated in stop-go manner (since the length was halved, 1 min rotation and 1 min stoppage). Keeping the motor speed at a very low value to achieve continuous rotation seemed not possible with available motor controlling means.

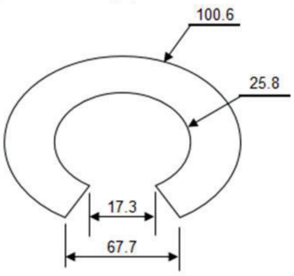
3.4.1 Inner Chamber

Fabrication of screw and its enclosure was the most difficult part because it involved complex geometries and tight tolerances. Violating those tolerances could have led to unpredicted biochar generation rate. Also, it deemed better to get an estimation of the magnitude of errors involved with the calculations, so further developments (mass manufacturing process of the reactor) could be more refined with the ability to achieve accurately predicted operational parameters. A mild steel solid shaft (dimeter 25.4 mm, 1.6 m in length) was taken as the screw shaft, while 1.2 mm gauge mild steel plates were used to develop the screw flight. According to the calculations, the screw was to be manufactured with the dimensions: pitch value 120 mm, screw diameter of 175 mm, and shaft length of 800 mm

(Figure 8(a)). After developing the flight profile using surface geometries, it was partitioned into 7 equal parts. Then the partitioned profile was flattened using the "Flatten" feature in SolidWorks as seen in Figure 8 (b). The idea was to cut 10 profiles from 1.2 mm gauge mild steel plate similar to the flatten geometry, using the wire EDM machine. Cut profiles were then formed into the spiral shape (according to the calculated pitch) and welded in series along the shaft. For the inner enclosure, a rectangular mild steel plate of 4 mm thickness was cut into a 900 mm× 612 mm rectangle and bent into an open cylinder using the three-roller bending machine.



(a)



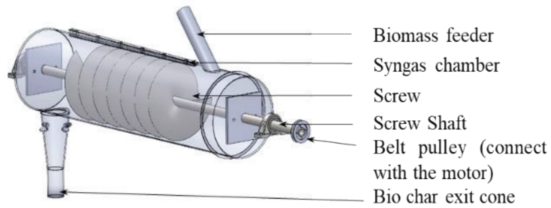
(b)

Figure 8 - (a) Screw Design (for the Prototype) with Basic Dimensions and, (b) Developed Planer Profile of the Flight

The design radial clearance of 10 mm between the screw and enclosure was achieved by keeping the inner diameter as 195 mm. The clearance was set to 10 mm at the design stage with the purpose of reducing any biomass chunks stuck between the enclosure and screw, which could ultimately obstruct the feeding process. The open cylinder was then directed to machining of feeding pipe connection hole and biochar exit hole. A slot opening for the syngas chamber was also cut accordingly. The screw was then placed inside the chamber and end cups were welded onto both ends. The fabrication of inner chamber was finalized by welding the feeding line attachments with 45-degree inclination, syngas chamber, and biochar exit cone onto the enclosure (Figures 9(a) and (b)).

The structure to support the pyrolysis reactor was built with clay bricks. In order to add mobility to the prototype, the whole structure was erected on a mild steel mounted on a palette. Air inlet holes, secondary air supply, and metallic mesh (Figure 10(a)) as the grate were included in the structure at predetermined design positions and heights as the construction progressed.

On top of the vertical front and back walls, the inner chamber was placed and construction was finished with the arc shaped top (Figure 10(b) and Figure 10(c)).



(a)

(b)

Figure 9 - (a) Design of the Inner Chamber and (b) Fabricated Inner Chamber Prototype (Biomass Feeder is not yet Mounted)

(a)

Figure 10 - (a) Fixation of the Steel Mesh to Act as the Grating System, (b) Fixation of Internal Chamber along with the Bearing to Aid the Screw Rotation, and (c) Completed Prototype

4. Results and Discussion

The fully fabricated prototype was subjected to a series of test runs in order to assess whether it would operate as predicted through the Ansys simulations. Thoroughly dried, crushed coconut shells were used as the fuel source. After spreading the 15 kg of shell fragments on the steel mesh, 0.25 litres of gasoline were sprinkled on top of them in order to vaporize any moisture on the surface. The effect of gasoline was calculated to be equivalent to additional 0.5 kg of coconut shells. As the biochar source, 15 kg of dried cinnamon sticks and corncobs were loaded into the internal chamber through the biomass feeder in subsequent test runs. The coconut shells were set to ignite, and the screw was set to rotate by powering on the motor. While a timer was running, the prototype was left untouched under constant monitoring for any malfunctions. The same process was repeated three times.

Even though the Ansys simulation was only run for 5 minutes until it reached the steady state, it was safely assumed that test runs would take significantly more time to achieve the same. In the simulation, a constant heat source of 800 ^{0}C was applied at the steel mesh base, which would immediately start the heating process. However, in the test runs, enough time was consumed for the initiation and progression of the pyrolysis process of the feedstock. The average runtime of all three test runs was calculated to be 2 hrs. During each test run, a TEMPSENS K type thermo couple with a long probe was used to measure the temperature values at several points. The probe was inserted through air intake openings and small pre-drilled holes on the outer chamber (Figure 11).

The temperature measurements were taken from six pre-decided locations (Figure 12). To ensure the results would represent an overall picture independent of slight variations in room temperature, humidity, and other atmospheric variations, they were measured through seven consecutive days. It is also worth noting that each reading was within ± 5 ^{0}C to each other, attesting to the fact that the minor variations in the operating environmental conditions do not have a significant effect on the performances of the reactor. Finally, the average temperature of all the measurements were carried out to further analysis. This would also assure an improved degree of repeatability compared to non-averaged values.

The comparison of the temperature values extracted from the simulation and measured through the temperature probe are tabulated in Table 2. The simulation and test run temperature values were found to be coinciding with each other within a maximum percentage error of 5% (Table 2). The average biochar yield from all three test runs was measured to be 4.8 kg and 4.2 kg for cinnamon and corncobs. Comparing to the weight of feedstock, it was a ~32% and 28% of yield for those biomass types. Therefore, it was concluded that the prototype fabrication is a successful attempt. Moreover, the potential of propagating the proposed design into an industrially capable biochar reactor was verified.

Type	K
Max Temp	~ 1000 ^{o}C
Manufacturer	TEMPSENS - India

Figure 11 - Taking Temperature Measurements Using TEMPSENS K Type Thermo-Couple

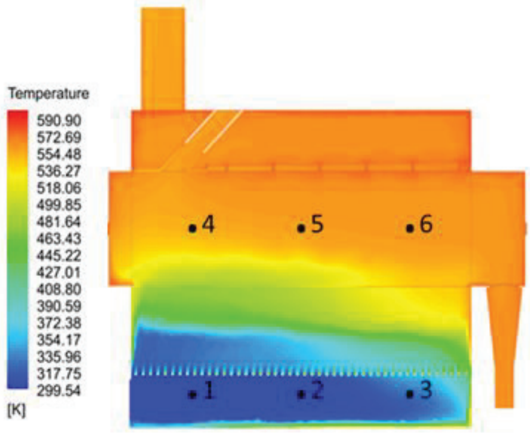


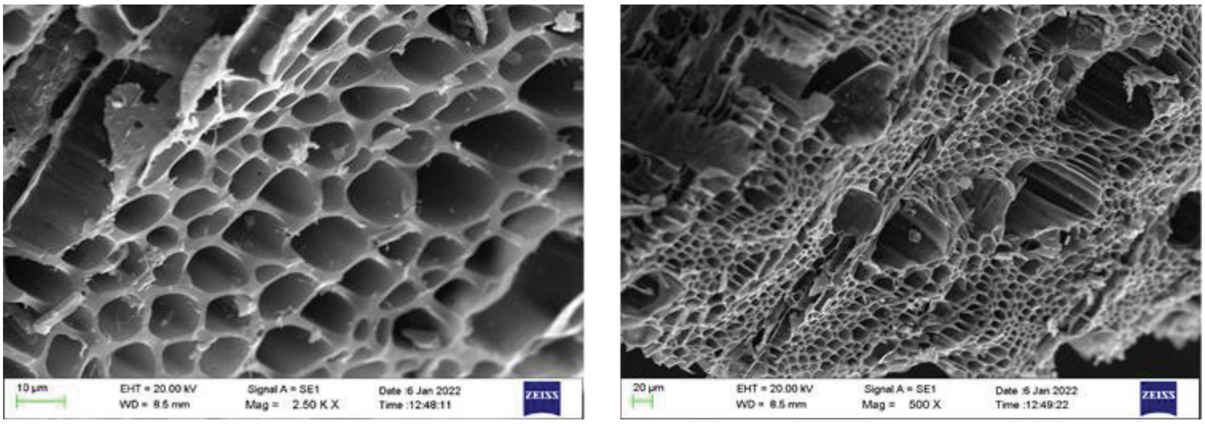
Figure 12 - Validation of the FEM Results with the Actual Temperature Measurements (Temperature Measurement Locations)

Table 2 - Measured and Simulated Temperature Values of Locations Depicts in Figure 12

Location	Ansys Simulated Temp. (^{0}C)	Measured Temp. (^{0}C)	Error (%)
1	299	285	5
2	321	305	5
3	485	470	3
4	541	524	3
5	573	564	2
6	545	528	3

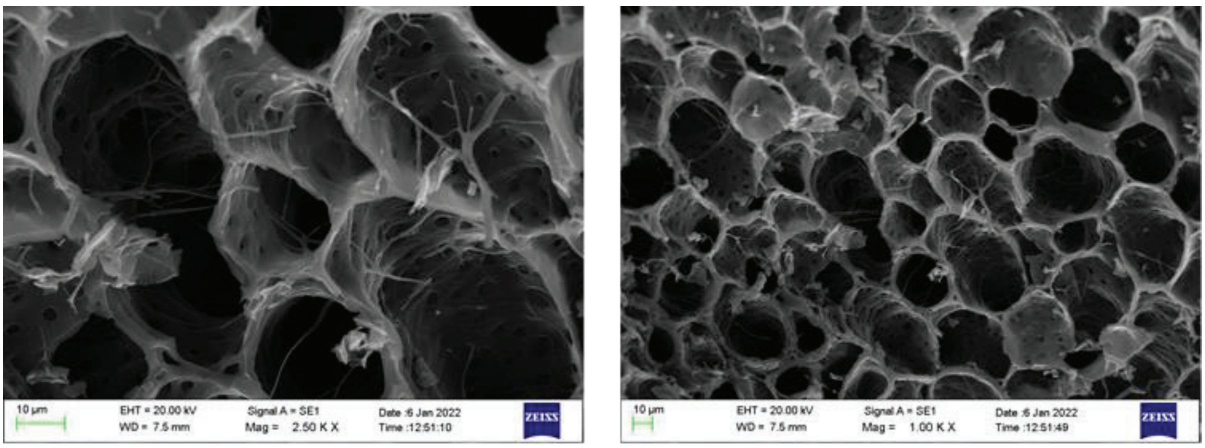
Moreover, few test runs were conducted with the same conditions to produce few biochar samples using cinnamon and corncobs as the initial biomaterial. For both biomaterials, inner chamber was kept at approximately 550 ^{0}C for about 2 hours of time enabling medium pyrolysis temperature and residence time conditions. The final samples were collected through the biochar exit cone of the design to a water bath to minimize the chances of the samples getting oxidization. Then the samples were tested for the inner structure using the ZEISS EVO LS15 Standard Electron Microscope (SEM) model. The image results for cinnamon biochar and corncob biochar are shown in Figures 13 and 14, respectively.

The structure of both biochar samples seems to contain a lot of porous cavities and hence a large surface to volume ratio. Among many applications, surface area and the porosity are considered as two of the most important properties of biochar. Having more active sites in the structure would eventually result in enhancing biochar properties such as cation exchange capacity, adsorption capacity and water holding capacity [30]. These figures show a clear distribution of pore sizes in the biochar structure produced using the proposed design in this paper. Macrospores in the structure are said to be conductive to the diffusion of substances while mesopores could act like mass transfer channels. Microspores in the structure exist to provide trapping spaces for the substances [31]. Due to this unique structure, when utilizing this product to create fertilizer layers, this could enable fast adsorption and slow releasing of agents enabling soil to contain nutrients in the long run. Moreover, a highly porous structure like this could easily retain water in the soil for a longer period of times. So, this biochar, produced through the proposed design under medium pyrolysis conditions of a temperature of approximately 550 ^{0}C and a residence time of 2 hours, would be a viable option in utilizing it as an agro fertilizer to maintain soil fertility even in extreme climate conditions.



(a) (b)

Figure 13 - Structural Morphology of Cinnamon Biochar Sample (a) ×2.5K Magnification and (b) ×500 Magnification



(a) (b)

Figure 14 - Structural Morphology of Corncobs Biochar Sample (a) ×2.5K Magnification and (b) ×500 Magnification

5. Conclusions

Concepts such as sustainable growth and food security are rapidly becoming mainstream topics in the current world. This compels the agricultural industries to progressively shed their malpractices and move forward with more environmental friendly and health-conscious technologies.

As a step toward sustainability for the Sri Lankan agriculture sector, this research was initiated with the objective of designing and developing a low-cost, efficient, industrial-scale biochar pyrolysis reactor for local use.

- The rapid degradation of soil quality cause by the prolonged use of chemical fertilizers could inevitably render fertile Sri Lankan agricultural lands useless in the long run. These adverse effects can be countered by using sustainable alternatives like biochar as fertilizers.
- Pyrolysis reactors are used to produce biochar. Due to the qualities like controlled operation, the auger pyrolyzing technique was decided to be integrated into the intended reactor design.
- After calculating the necessary dimensions of the components through initial parameters like biochar production rate, Dassault SolidWorks software was used to develop the design.
- The operation of the finalized model was simulated through the Ansys Fluent software. 800 ^{0}C constant heat source was defined at the bottom and simulation was ran allowing enough time to reach steady state conditions.
- After several cycles of identifying design flaws through the simulation, modifying the solid model accordingly, re-simulating was carried out to finalize the optimal design. The simulation of the optimal design suggested that the outer wall of the screw chamber that contains biomass reaches nearly 500 ^{0}C temperature in the steady state. Since that temperature is enough to carry out the pyrolysis process, the optimal design was verified to be working flawlessly.
- Owing to the limited budget and time, a scaled-down prototype was fabricated to carry out the real-life testing. Three test runs for each type of bio masses were carried out with 15 kg cinnamon and 15 kg of corncobs as the feedstock, and 15 kg of crushed coconut shells sprinkled with 0.25 litres of gasoline as fuel.
- The average biochar yield was measured to be 32% and 28%, respectively, for cinnamon and corncobs, within 2 hrs of run time. To further validate the temperature distribution resulted from the Ansys simulation, temperature values of six different points were read through a temperature probe. The test run temperature readings aligned with the corresponding Ansys measurements within a 5% error. Therefore, the prototype was further verified to be successful. Subsequently, the designed biochar kiln was confirmed as a successful attempt.
- The SEM images of the internal and surface structure of both obtained corncobs and cinnamon biochar samples structure show a significant distribution of pores in different scales throughout the section. This could well be utilized to serve the purpose of using this product as a soil amendment to create biochar layers in the soil.

6. Future Work

This initial research should be further broadened through some significant focusses identified by authors.

- For the moment, the combination of an electric motor and a reduction gearbox facilitates the automated rotating action of the auger screw. However, tasks like loading fuel, loading biomass, and unloading biochar are carried out manually. With further modifications, the designed kiln should be developed into a fully automated state.
- The test runs were conducted using cinnamon sticks and corncobs. The prototype should be put through further test runs with other biomass types.
- The allocated budget was not adequate to extend towards this testing. As for the prototype, the total cost was approximately under 80, 000LKR. Extensive tests should be carried out to test the quality of biomass yield from both feedstocks, in terms of critical characterization and other chemical and physical properties.
- Testings can be extended by altering parameters like fuel type, percentage opening of primary air inlet, and moisture content of biomass. The purpose of this testing should be identifying several optimal operational configurations for the pyrolysis reactor.

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