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Pyrolysis in Fecal Sludge Treatment

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ABSTRACT

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Excreta is an indispensable part of human everyday life. If these fecal sludges are not managed properly and discharged into the environment, they can cause severe waterborne diseases as well as water pollution that deteriorates public health and the living habitat.

Pyrolysis, a process of thermal decomposition of organic materials under the inert condition in an oxygen-deficient environment, is a potential fecal sludge treatment with marketable byproducts, especially biochar.

The main objective of the thesis was to conduct a literature survey and make a comparison of different technological options of pyrolysis use in fecal sludge treatment. Three different pyrolysis uses in fecal sludge treatment were analysed: Sol-char toilet, an onsite treatment integrated with pit-latrine for household use, a small scale biochar reactor to serve a community of 100 people in Kenya and the industrial scale Greenlife pyrolysis plant.

The results show that all the pyrolysis technologies produce 100% pathogen elimination. Hygiene is satisfied and equal for all meanwhile the pyrolysis plant is dominant when the criteria are effectiveness, odor emission control and sustainability. Besides, the innovative use of solar energy powering pyrolysis design poses a great idea for sustainable development. Production cost overlaps the byproduct benefit and more improvement is required to minimise price and for long-term investment to be profitable.

In conclusion, these three cases with different pyrolysis scales and technologies have both pros and cons. However, through the literature review of the three cases in specific and the pyrolysis fecal sludge in general, pyrolysis technology has proved to be feasible as a sanitation solution for fecal sludge treatment and potential energy recovery via biochar and syngas production. To better understand the potential of fecal sludge pyrolysis to safely and cost-effectively determine the technical feasibility and financial resource requirement of implementing pyrolysis as a fecal sludge treatment process, further improvement studies and experiments are needed.

Key words: pyrolysis, fecal sludge, biochar, sustainability

CONTENTS

ABBREVIATIONS AND TERMS

FS	Fecal sludge
FSM	Fecal sludge management
HSM	Human solid waste

1 INTRODUCTION

1.1 Current fecal sludge treatment situation

Excreta is an indispensable part of human everyday life. Indeed, 130 g of feces and 1.4 L of urine every day are produced by an adult (Rose et al. 2015). Fecal sludge (FS) is a slurry or semisolid resulted from the collection, storage, or treatment of combinations of human excreta (feces and urine) and black water such as toilet wastewater (Harada et al. 2016). With an estimation of 7 billion people on Earth nowadays and the keep growing population number, tons of fecal sludges will need to be treated daily. However, that is not the case for 2.4 billion people worldwide who still have to live without access to sanitary toilets (UNICEF & WHO 2015), and even for where improved on-site technologies are applied to contain excreta because the level of quality and access to fecal sludge management (FSM) services for the emptying, conveyance, treatment and disposal of the resulting fecal sludge in most of the countries is usually limited. Therefore, the safely treated and recovery possibilities of FS today are much smaller than its potentials.

A wide range of technologies developed for safely managing human waste includes pit latrines, septic tanks, and sewer systems along the sanitation service chain as demonstrated in Figure 1. Networked sewerage is considered as the preferred sanitation solution whereby excreta and associated wastewater are transferred through a network of pipes to the wastewater treatment plants. Nevertheless, access to a sewerage system is narrowed or even non-existent in many developing countries because of the cost-effective issues in many situations. Meanwhile, most people are using alternative non-networked sanitation options where human waste and wastewater are released into a septic tank or pit or even directly into a drain, river, sea, or open ground. (UNICEF & WHO 2015)

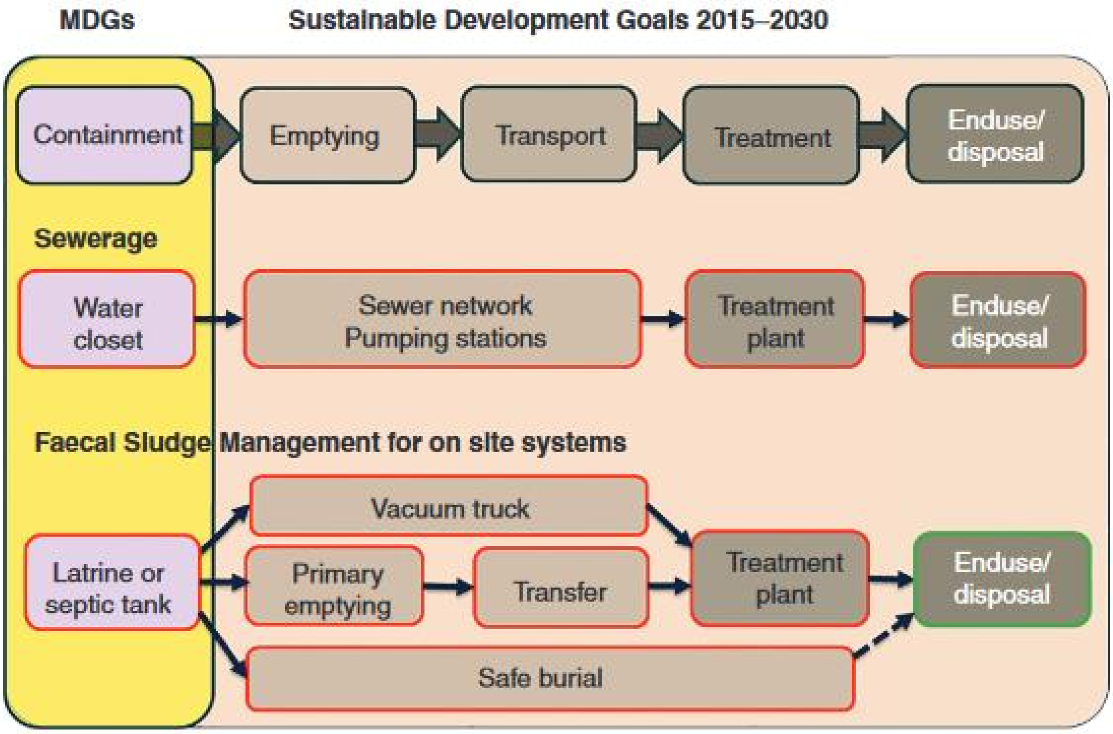


FIGURE 1. Sanitation service chain of on-site sanitation technologies and centralized wastewater management technologies (Harada et al. 2016)

The problematic part of the non-networked system is that the fecal sludge collected from onsite facilities rarely reaches a treatment plant for safe disposal or reuse possibilities. The consequence is direct discharge into the environment that can cause severe waterborne disease and water pollution that deteriorates public health and the living habitat. Moreover, it also contributes to the fact that 0.7 billion people in the world still do not have access to safe drinking water meanwhile the precious water is polluted with human excreta (Harada et al. 2016). Hence, an innovation in the FSM and treatment technologies need to be developed further from the current situation to keep up with the global need for leveraging the sanitation standard. It is not only for the safe management and pollution prevention but also for the potential resources' recovery from FS.

Indeed, human waste and FS contained valuable nutrients and energy potential that can be recovered by many recovery technological options. Other than recognized forms of recovering nutrients (protein, carbon, phosphorous, etc), resource recovery can be heat or energy from biofuels. (Strande et al. 2014)

Pyrolysis, biodiesel, pelletized, anaerobic digestion, and incineration are famous technologies to take advantage of FS energy potential. With the global energy shortage challenge, every option for energy recovery is concerned and FS treatment may be a promising one in the future. The economic benefit from nutrients and energy recovery from fecal sludge is not just from its end product value but also the sustainable development of FSM by offsetting a portion of the treatment and disposal costs (Harada et al. 2016).

The promising resource recovery potentials from FS is undeniable and need to be researched more for further large-scale deployment. However, the challenges remain that are to make end-products from FS recovery technologies acceptable for use and also market-attractive in terms of both price and demand. Besides, the value of resource recovery from FS must not be overlooked the sustainability of FSM in every country.

1.2 Pyrolysis in fecal sludge treatment

Pyrolysis is a process of thermal decomposition of organic (carbon-based) materials under the inert condition in an oxygen-deficient environment. Pyrolysis takes place due to the weak thermal stability of chemical bonds of materials that allows them to be disintegrated by using the heat. It simultaneously involves the transformation of the physical phase and chemical composition to form the new molecules. (Zaman et al. 2017)

Pyrolysis products include solid (biochar), liquid (bio-oil), and non-condensable gases (H2, CO2, etc). Its products have many practical values, for example, biochar can be used as a soil amendment to increase plant growth yield, bio-oil can be transformed to special engine fuel, or through gasification processes to a syngas and then biodiesel, finally, the gases can be utilized as combustion fuels. (Zafar 2009)

Pyrolysis reactions can be characterized in two types which are fast pyrolysis and slow pyrolysis. During the fast pyrolysis process, biomass is rapidly heated to temperatures of 650 to 1000°C in seconds. This process is primarily used to produce bio-oil and gas. Slow pyrolysis is in contrast with long solids and gas residence times (range from minutes to days and over five seconds, respectively), low temperatures, and slow biomass heating rates ranging from 0.1 to 2°C per second and the prevailing temperatures are nearly 500°C. (Zaman et al. 2017)

A typical pyrolysis system unit involves the facilities for lignocellulosic residues pre-processing, the pyrolysis reactor, and subsequent unit for downstream processing. It can be characterized mainly as units that produce only heat and biochar (slow pyrolysis) or units that produce biochar and bio-oils (fast pyrolysis). The simplified model for these two units is illustrated in Figure 2 below.

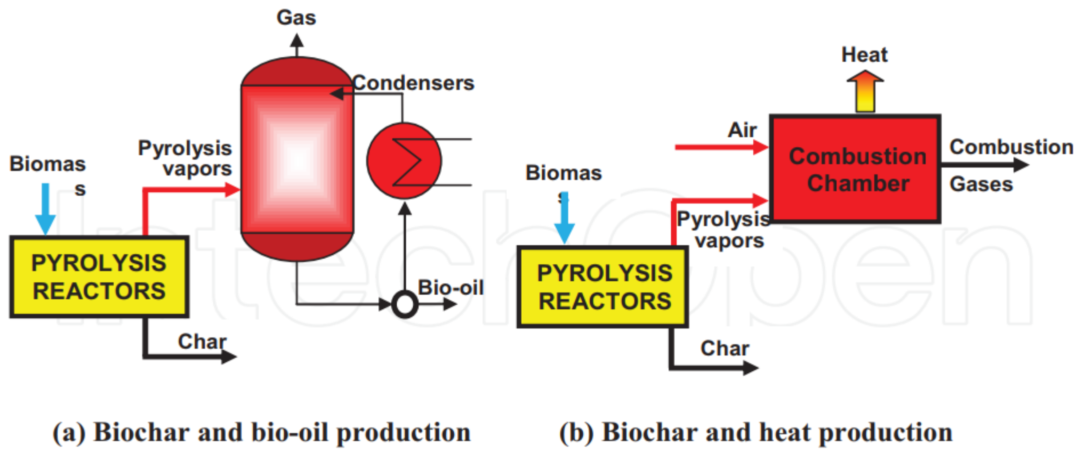


FIGURE 2. Simplified flow diagram for typical pyrolysis unit (Zaman et al. 2017)

Fecal sludge is a potential feedstock for pyrolysis process thanks to its high organic content. However, the efficiency of the pyrolysis process depends a lot on the moisture content of the feedstock, which should be around 10%. Indeed, at higher moisture contents, high levels of water are produced and at lower levels, there is a risk that only dust instead of oil is produced (Zafar 2009). Therefore, with the high-moisture value of the fecal matter, FS treatment pre-processing must require drying to the desired level before exposure to the pyrolysis environment.

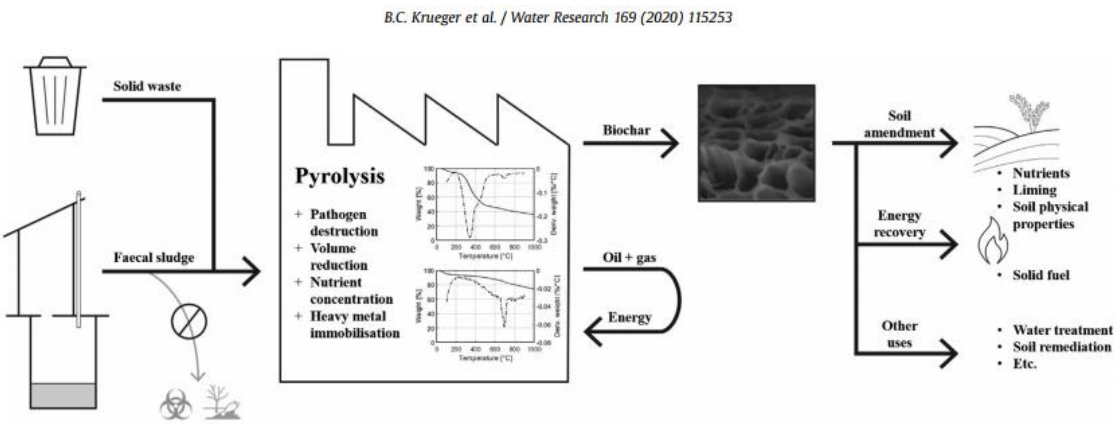


FIGURE 3. Conceptual diagram of biochar production for fecal sludge treatment (Krueger et al. 2019)

Pyrolysis in FS treatment is not only offering a viable alternative to illegal dumping and provide safe handling but also taking the advantage of energy and nutrient recovery potentials from FS, especially biochar production. Figure 3 demonstrates the overview diagram of FS treatment and the advantages associated with biochar production from FS.

In comparison to other biological or physical treatment methods, the short retention time of a continuous pyrolysis process helps lower space requirements. Moreover, throughout the pyrolysis process, storage, transport, and disposal of the products simplified through reduced volume and biochemical stability. The option to co-treat FS with other waste fraction is also possible. Considering that other carbon sources like organic waste and low-grade plastics are problematic issues in the waste management of low- and middle-income countries, co-treatment should be a promising solution. (Krueger et al. 2019)

More importantly, the FS pyrolysis process results in pathogen destruction due to high processing temperatures that help ensure the hygiene of FS treatment outputs (Ward et al. 2014). It is also a great advantage for the agricultural utilization of biochar produced from FS as it may improve physiochemical soil properties and add to the value from any plant nutrients retained in the biochar like phosphorus and potassium. Biochar uses allow for soil amendment, fuel, adsorption media, and Carbon sequestration (Krueger et al. 2019).

Although pyrolysis is a promising alternative solution for FS treatment, previously, research on FS biochar production has only been at a laboratory scale. The demonstration of FS treatment technologies for resource recovery at full scale is essential to be able for scaling to occur rapidly, to keep up and deal with the sanitation crisis. To learn from the past knowledge and to be able to develop it beyond, the review of the current technological option in FS treatment is needed.

1.3 Aims

The main objective of the thesis is to conduct a literature survey and make a comparison of different technological options of pyrolysis use in fecal sludge treatment with different moisture contents. It is an applied study based on the related existing knowledge from research results, scientific reports, and journals to search for the efficient and sustainable pyrolysis treatment method. Through the research review, further analysis, drying methods and possible improvements of the pyrolysis treatment or combination of methods will also be discussed in the thesis.

Moreover, from the real case study that represents different options of pyrolysis use in fecal sludge treatment in different conditions, the thesis purpose is to study the local adaptability and feasibility of the pyrolysis technology, analyze the pros and cons and conclude the lessons learned from the practical application for further development.

2 METHODOLOGY

2.1 Method and scope of the work

The literature review is conducted by searching for information through the internet database. All the data was collected from the desk research through various search engines (Google Scholar, TuniLib/Tampere University Library, Science Direct, Research Gate, etc.) with respect to professional research works, books, articles, newspapers that concern the topic.

The scope of the work covers the use of pyrolysis in fecal sludge treatment research, experiments, and potential applications worldwide. Since pyrolysis in fecal treatment has not yet been utilized widely in large scale and commercial operation and still in the research and development phase, the analysis and comparison of the technological options for pyrolysis application will be discussed as the specific real case studies and projects that are experienced, researched and developed in the world. The promising and innovative pyrolysis techniques applied in the well-known projects will be presented in this thesis work and its scope and scale may vary following every single case.

2.2 Assessment criteria

For the evaluation of the pyrolysis technological uses in fecal sludge treatment, a list of assessment criteria is illustrated below as a background for the comparison. The main factors and focus area of criteria may vary due to specific cases investigated. The criteria are shown in the order of their importance in this work.

2.2.1 Effectiveness

Considering the effectiveness of the technological option, the efficiency of the process is the most crucial issue which concerns the operational efficiency, by-products yield, and its quality. Moreover, it is also important to know the impact of external factors (temperature, weather, etc) on the process to ensure the constant quality of products. Another concern is the scalability of the technique, whether the pyrolysis treatment method has any limitation for generally applicable and scalable worldwide, whether it requires any special conditions for the location or the input fecal sludge quality.

2.2.2 Hygiene

When it comes to hygiene, the pyrolysis process must meet the requirements accepted by governments. The hygiene of the by-product must also be guaranteed. Throughout the operation, the processed matter must be free of pathogens, bacteria, and other biological pollutants.

2.2.3 Odor emission

The odor is one of the problematic issues for fecal management that is very sensitive to the public and nearby area from the treatment unit. Therefore, during the pyrolysis treatment, odor emissions when processing the fecal matter have to be minimized as much as possible. It also must meet the regulation for allowed odor emission value.

2.2.4 Sustainability

The life cycle assessment of the pyrolysis treatment process must be taken into account. Construction, operation, or product storing may have some impact on the environment by releasing harmful substances. These effects could lead to further treatment for odor, air, soil, or water.

2.2.5 Cost

The cost analysis is an important practical matter to scale and apply the technology widely as well as attract the investors and the market. These costs include the construction and operation costs of the process itself, and also other maintenance and other further development costs. The acquisition costs to replace the existing system into the new pyrolysis treatment unit will not be considered.

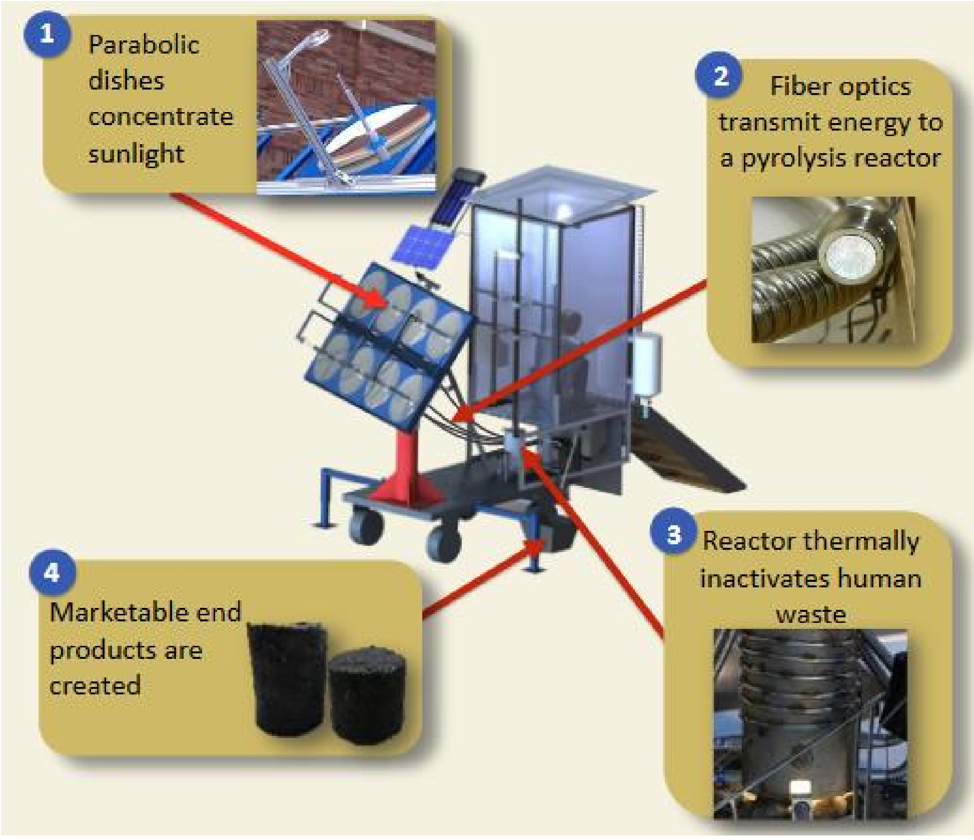
3 CASE STUDY

3.1 Solar-assisted pyrolysis (Sol-char toilet)

A team of scientists and professors from the Environmental Engineering and Chemical Engineering Department at the University of Colorado in the USA received sponsorship to develop a new toilet design to tackle the sanitation challenge in the developing countries. The solution does not depend on the existing sewer, piped water, or energy infrastructure whose systems of the poor countries are lack of and it can process human waste and transform it into a useful resource at a limited cost to the user. This interesting solution is solar-assisted pyrolysis as known as Sol-char toilet which takes advantage of the solar radiant as a thermal source for the pyrolysis process.

3.1.1 Model

Sol-Char toilet model is a combination and integrated solution of the pit latrine and pyrolysis system that utilizes the parabolic dishes to concentrate sunlight and make it as a thermal source for the pyrolysis reactor. Solar thermal energy is transmitted through fiber optics to the reactor where fecal sludge is processed at high temperatures in the absence of oxygen condition and transformed into useful and pathogen-free biochar (Figure 5). (Ward, B.J et al. 2014)



FIRGURE 5. Sol-char sanitation prototype (Ward, B.J et al. 2014)

By capturing the sunlight to power the pyrolysis reactor, the process helps to reduce the fecal feedstock into promising marketable end products that are biochar and high-energy syngases. Indeed, the biochar product includes inorganic components, organic. The gas products mostly are CO2, etc. The potential uses of biochar are proved as a value-chain for toilet byproducts, especially for soil amendment to help increase yields in soils and improve poor, sandy, and acidic soils, nutrient-enriched biochar fertilizer and for solid fuel production such as charcoal briquettes to be used as heating or cooking fuel. This is a lucrative and sustainable way to minimize the cost of sanitation systems by valuing its byproducts. (Ward, B.J et al. 2013)

3.1.2 Results

Because the solar-assisted reactor was still under prototype development at the time of experiments, the expected pyrolysis efficiency test was conducted in the laboratory and the fecal biochar was manufactured in a simulation pyrolysis chamber with temperature control.

Two separate experiments were run to examine the characteristics of fecal sludge pyrolysis byproducts and its energy content. The first experiment utilized fecal sludge from volunteers that were dried and grounded to smaller than 400 μm in size and then pyrolyzed at 300°C and 500°C with the hold time of 7.5 hours at the target temperatures (Ward, B.J et al. 2014). The result of the byproducts characterization is illustrated in the table below.

TABLE 1. Characterization of fecal sludge pyrolysis byproducts (Ward, B.J et al. 2014)

Temperature (°C)	Char yield (%)	Tar yield (%)	Gas yield (%)
300	55,6 ± 3,1	33,0 ± 5,4	10,4
500	48,0 ± 3,5	26,7 ± 2,5	26,3

The result shows that the higher temperature, the more gas produced and the lower temperature, the more char will be yielded. Considering the preference of byproducts benefits, the temperature can be adjusted to produce the wanted outcome which is biochar in this case.

The feasibility of using feces-derived biochar as a solid fuel for heating and cooking is an essential study because of its robust demand in the developing countries where the model implemented. To assess the energy content of the biochar, the reactor was set to pyrolyze real dried fecal matter samples stored in a freezer for a maximum period of two weeks before pyrolysis at the temperatures of 300, 450, and 750°C. The temperature increase rates of the feces were also monitored. When the fecal internal temperature reached the target temperature, that temperature was held for 2 hours (Ward, B.J et al. 2013). The higher heating value of biochar produced at those temperatures was determined by using a Parr oxygen bomb calorimeter and results are presented in Figure 6 below.

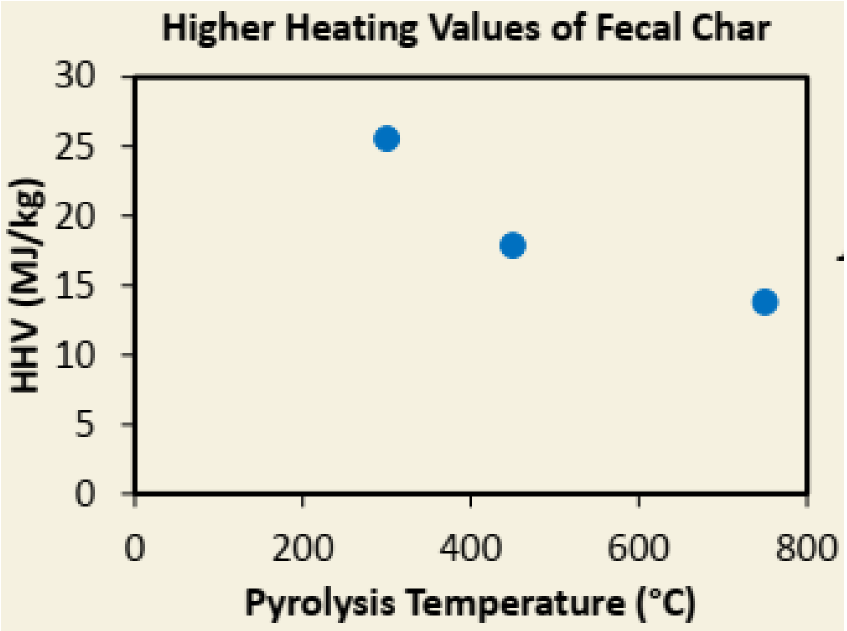


FIGURE 6. Higher heating values of fecal char in accordance with pyrolysis temperature (Ward, B.J et al. 2014)

In general, biochar made from feces has a higher heating value smaller than 25.6 MJ/kg whereas fecal biochar produced at the lowest pyrolysis temperature contains the highest energy content and vice versa. Fecal biochars product at 300°C were similar in energy value to wood biochars and bituminous coal (Figure 7), obtaining a higher heating value of 25.6 MJ/kg, while fecal chars produced at 750°C were notably lower in energy content at 13.8 MJ/kg.

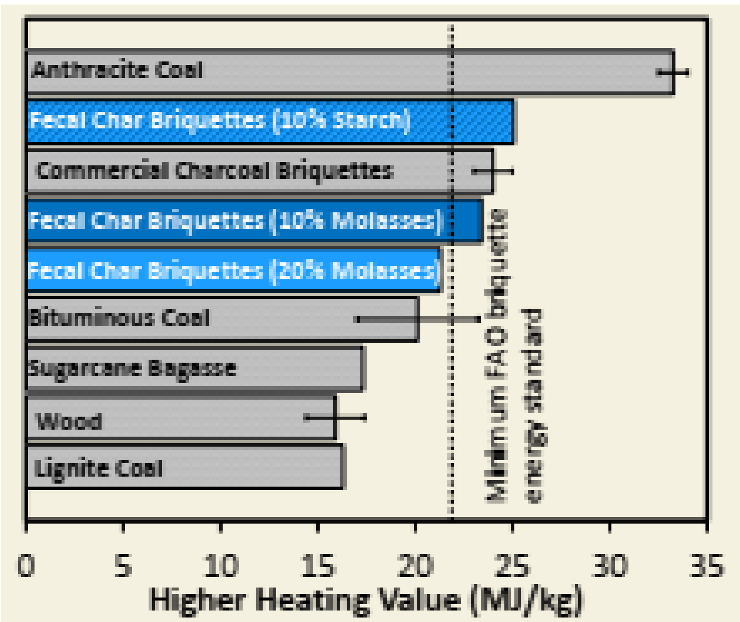


FIGURE 7. The higher heating value of common solid fuels and human fecal char briquettes manufactured in this study (Ward, B.J et al. 2014)

Figure 7 illustrates the higher heating value of common solid fuels and human fecal char briquettes produced in this experiment. In comparison with the literature data, the potential energy revised content of fecal char briquettes proves its competitiveness to the commercial charcoal briquettes market.

3.2 Development of human solid waste to biochar reactor in Kenya

Stanford University in cooperation with the Climate Foundation started developing a prototype biochar reactor in Nairobi, Kenya to efficiently convert human solid waste to biochar in the effort to improve and reinvent the sanitation system in the inadequate conditions without grid power and water in Africa.

The Stanford University and Climate Foundation team have designed, manufactured, assembled, experimented, and refined a biochar reactor that is capable of handling human feces of 100 people per day. The main objectives of the project are to safely handle human solid waste (HSW) with a minimum amount of supplemental fuel and to maximize biochar yield from the pyrolysis reactor as a function of moisture level for the input HSW. (Herzen & Talsma 2014)

3.2.1 Model

The biochar reactor model is developed as an integration of the continuous processes from pre-drying, pyrolysis, combustion, heat exchange to odor elimination which includes the following components: a dryer/dewatering, solid-gas separator, pyrolyzer, gasifier, combustor, biochar collector, and heat exchanger. The assemble biochar reactor in real life is showed in the picture below.

PICTURE 1. The assembled biochar reactor (Gates 2012)

The integrated different subsystems form a complete and close loop reactor that can process human solid waste to biochar and recover energy to input itself. The description of the reactor sub-processes, its functions, and output are presented in Table 2.

TABLE 2. Reactor sub-processes (Herzen & Talsma 2014)

Sub-Process	Purpose	Example Input	Example Output
Dryer / solids preheater / Dewater	Reduce moisture content of incoming material	Human waste at 75 % moisture & air at 105 ˚C	Partially dried human waste with 40% moisture, humidified air
Pyrolyzer	Establish chemical equilibrium at a given temperature, pressure	Partially dried human waste	Syngas, biochar, & ash
Gasifier	Establish chemical equilibrium at a given temperature, pressure	Partially dried human waste and a sub-stoichiometric volume of air	Syngas, biochar, & ash
Combustor	Establish chemical equilibrium at a given temperature, pressure	Syngas, raw greenwaste and excess air	Combustion products (CO_2 & H_2O)
Heat Exchanger	Transfer energy from hot exhaust stream to cold inflow stream	Ambient air and combustion exhaust	Hot air and cool combustion exhaust

In the design model illustrated in Figure 8, pre-drying technology enables higher moisture feedstock human waste at 75% to be dried to 40% that is efficient to be continuously processed in a smallscale pyrolyzer to produce biochar and synthesis gas. The syngas and biochar output are then separated to went through other subprocesses. The syngas is delivered to the combustor where it can be burned with additional green waste. These hot combustion products can be used as a thermal supply for the pyrolyzer reactor as well as pre-heat air for the drier. The biochar is collected and then run through the odor elimination process with biochar activated carbon filter before it gets ready for the agricultural uses. Besides, the biochar reactor features a counterflow heat exchanger that recuperates thermal energy in the exhaust by transporting it to the intake air, hence help to conserve energy and making the biochar production more efficient. (Herzen & Talsma 2014)

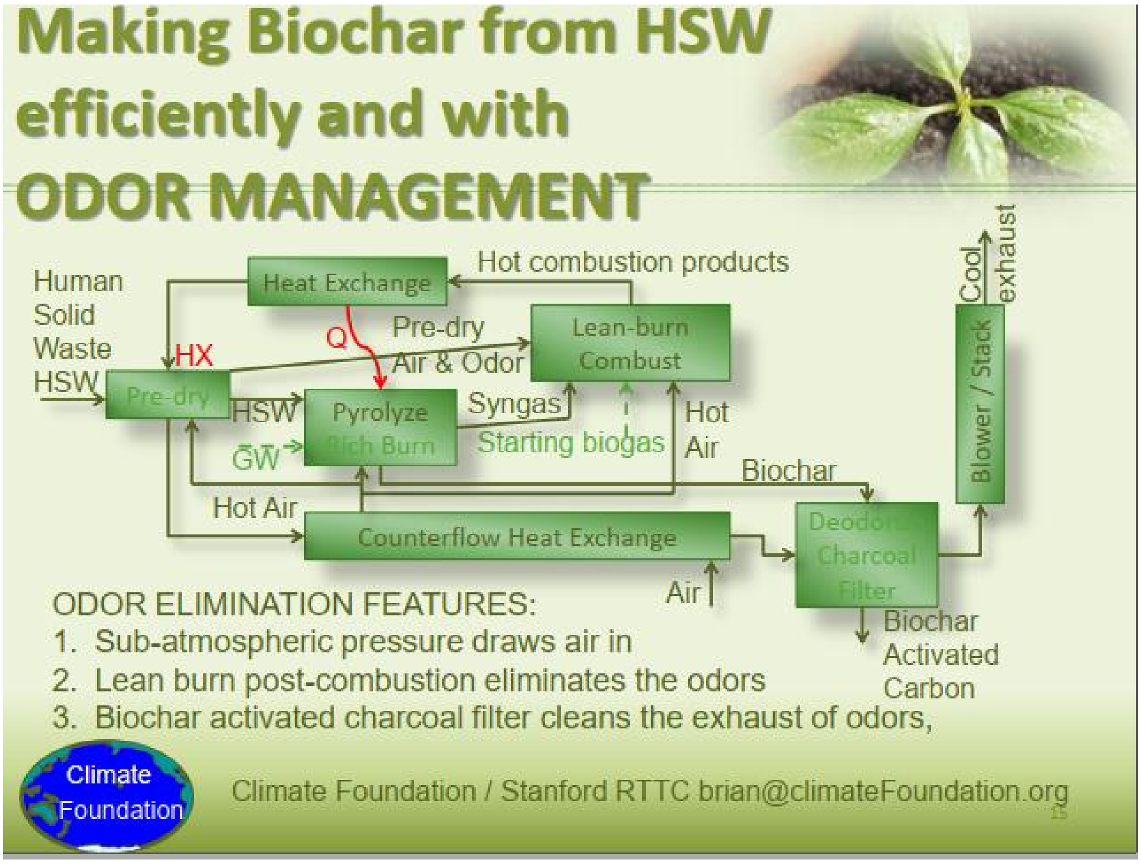


FIGURE 8. Model of biochar production from human solid waste (Herzen 2012)

When it comes to operational energy efficiency, the main thermal source for the biochar reactor derives from the combustion of the syngas produced from the HSW when it is pyrolyzed. The resulting enthalpy is then transferred from the lean-burn combustion chamber back to the pyrolysis chamber through the heat exchangers. The system energy efficiency is achieved through the combination of counterflow heat exchange in the core pyrolyzer and the exhaust heat recuperation subsystems. Other supplemental fuel sources for the reactor startup contains biochar, propane, and natural gas. (Herzen & Talsma 2014)

3.2.2 Results

According to the literature, fecal sludge output per capita is 135-400 g/day. Using the geometric mean of 232 g/day per capita, 100 people/day results in 23.2 kg/day throughput, or just less than 1kg/hour. The biochar reactor system demonstrations have validated biochar reactor operation at input rates of approximately 2 kg/hour and proved its productivity to serve the HSW treatment for a community of 100 people. (Herzen & Talsma 2014)

By heating an appropriate flow of input fuel sources to high temperatures above 450ºC for about 15 minutes, the biochar produced from the reactor is 100% pathogen-free and odorless thanks to the separated odor elimination subprocess that make it suitable and ready to be used for agriculture purposes (Picture 2).

PICTURE 2. Biochar resulted from the reactor (Herzen & Talsma 2014)

The model was tested under the conditions listed in Table 3 below. The test aims to determine the impact of the varied properties of the human solid waste (HSW) heating value and moisture content on the operation. By operating the biochar reactor with NASA HSW simulant and zero green waste input, the minimum energy inputs required to run the biochar reactor can be defined.

TABLE 3. Model condition (Herzen & Talsma 2014)

Pyrolysis Temperature: 550°C	GreenWaste Flow to Combustor: 0 kg/hr
Human Waste Flow: 10 kg/hr	Weight Fraction of Biochar & Ash: 10%
Heat Exchanger Effectiveness: 80%	Oxygen Concentration in Exhaust: 3%
GreenWaste Flow to Pyrolyzer: 0 kg/hr	Pinch Point: 10°C

The calculation results illustrated the plot of the required airflow for a given moisture level and heating value of HSW in Figure 9. The calculations were made base on the operating region, excess energy at a given set of operating conditions, syngas heating values, and required airflow for the completion of syngas oxidation (Herzen & Talsma 2014).

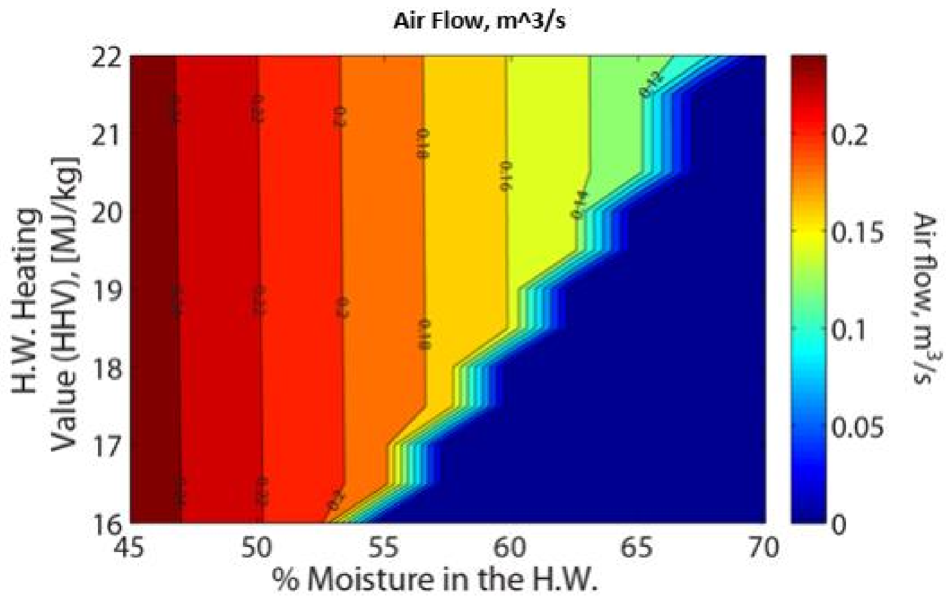


FIGURE 9. Plot of required airflow for given moisture level and heating values (Herzen & Talsma 2014)

The operating point is feasible when the heating values of NASA HSW simulant input are 20-22 MJ/kg and its moisture content is at approximately 60% level whereas airflow and excess energy value are appropriate for the operation. These limits on water content and heating value can be improved when operating with a majority of HSW and a minority of green waste at such moisture levels. For example, HSW at 75% moisture can be mixed with a smaller amount of green waste at 35% moisture content for average moisture content of 55-60%. (Herzen & Talsma 2014)

3.3 Greenlife pyrolysis plant

In normal conventional waste treatment plants, waste nutrients such as carbon and nitrogen are transformed into CO2, etc, and cannot be utilized as soil fertilizers because. If the sludge is burned afterward, the phosphorus nutrient is also wasted. Resources are dwindling and need to be reserved by any means necessary. The Greenlife pyrolysis plant design with an innovative pyrolysis process is saving these nutrients by transforming energy-rich sewage sludges into valuable carbon-phosphorus fertilizer. (Greenlife resources GmbH 2018)

This process is proved to consume less energy than conventional techniques of the waste treatment plant that helps to decrease CO2 emissions and was awarded the Austrian Climate Protection Prize 2012 (Greenlife resources GmbH 2018).

3.3.1 Model

The Greenlife pyrolysis plant is designed into four different sections with the integration of functions which are drying, feeding, pyrolysis reactor, and biochar bucker that create a complete and continuous workflow of the plant (Figure 11). The detailed model of the pyrolysis production line is presented in Figure 10.

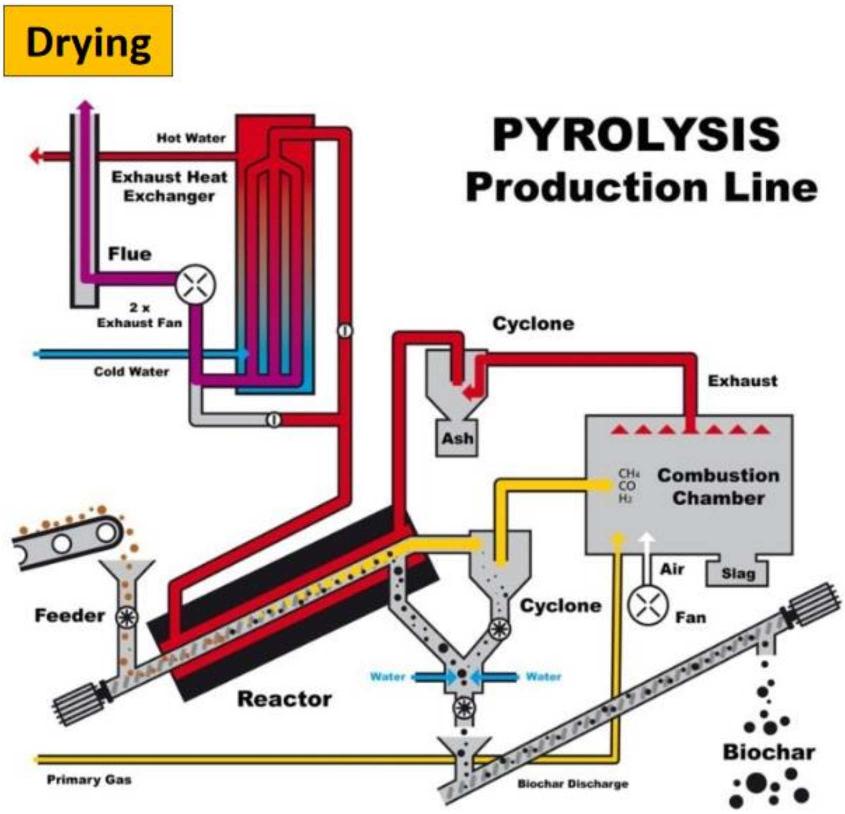


FIGURE 10. The operation model of pyrolysis in sewerage sludge treatment (Greenlife resources GmbH 2018)

FIGURE 11. Pyrolysis plant workflow (Greenlife resources GmbH 2018)

Section 1, drying: In this stage, after dewatering, the sewage sludges of about 25 % dry matter content are dried to an estimated 65% dry matter. The waste heat from the reactor is used to process this stop. The drying is a close loop process so that there is no odor emission leaked out. (Greenlife resources GmbH 2018)

Section 2, feeding: The dry matter is then loaded by wheel loader into the feed bunker and delivered automatically through a scraper floor in the distributor bunker. From there, the dried sludge is conveyed with a conveyor screw and via a rotary feeder to go into the pyrolysis reactor. (Greenlife resources GmbH 2018)

Section 3, pyrolysis reactor: The dried sewage sludge is transported through the reactor with a double screw and heated with the thermal source from the exclusion of air to 600 degrees Celsius. The syngas resulted in the pyrolysis process is then extracted and fed into the combustion chamber. The hold time of material in the reactor is 30 minutes to ensure that hormonal contaminations are eliminated. The remaining pure carbon formed is passed through a water spraying system and then conveyed via a rotary feeder and a discharge screw in the biochar bunker. The syngases formed are burned in the combustion chamber at 1,100 degrees Celsius, and the flue exhausts are cleaned by a further cyclone. After that, the hot gases stream is passed through the jacket of the reactor to heat the dry sludge that has just been introduced in the reactor. In a subsequent heat exchanger, the residual heat of about 100 to 150 kW is used for the primary thermal drying of the sewage sludge. (Greenlife resources GmbH 2018)

Section 4, biochar bunker: The temporary storage for biochar resulted from the process before it is used in soil amendment or other purposes (Greenlife resources GmbH 2018).

3.3.2 Results

As a result of the pyrolysis process, Greenlife plant can treat 4.000 tons of dewatered sewage sludge per year, with 25% dry matter. The biochar production is 70 kg/hour or 500 tons/year of pure biochar with the limitation of operation for the feedstock with humidity below 50% and a heating value higher than 6 MJ/kg. The costs for sewage sludge disposal can be minimized and offset by the lucrative biochar production. (Greenlife resources GmbH 2018)

The detailed technical datasheet for the Greenlife pyrolysis plant is illustrated in Table 4 below.

TABLE 4. Greenlife pyrolysis plant technical data (Greenlife resources GmbH 2018)

Technical data	Value
Capacity	4.000 t dewatered sewage sludges with 25 % dry matter per year
Disposal of sewage sludges per plant	up to 50.000 population equivalents (p.e.)
Production biochar	up to 70 kg/h or 500 t/year (depending on fuel selection)
Nominal fuel capacity	up to 500 kW per plant
Maximum operation limits	calorific value > 6 MJ/kg, humidity < 50 %
Thermal output	up to 150 kW exhaust gas heat (depending on fuel selection)
Power input	approx. 7,5 kWel
Weight of reactor	approx. 10 t
Dimensions of reactor	installation in 20-feet-container (approx. 8m x 2,5m x 2,5m)

4 COMPARATIVE STUDY

Throughout the analysis of three different pyrolysis uses in fecal sludge treatment, Sol-char toilet, an onsite treatment integrated with pit-latrine for household use, biochar reactor to serve a community of 100 people in Kenya and the industrial-scale Greenlife pyrolysis plant, the overall comparison of these pyrolysis technologies are examined based on five assessment criteria and its results are illustrated in Table 5.

TABLE 5. Overall comparison of the pyrolysis technologies between the cases study

	Effectiveness	Hygiene	Odor emission	Sustainability	Cost
Sol-Char toilet	+++	+++++	++	++++	++
Biochar production from human solid waste in Kenya	++++	+++++	++++	+++	++
Greenlife pyrolysis plant	+++++	+++++	+++++	+++++	+++
+ Very poor; ++ Poor; +++ Moderate; ++++ Good; +++++ Very good					

Firstly, using pyrolysis technologies for fecal sludge treatment in general and these three cases in this study in specific possess strong results in terms of hygiene. By pyrolyzing the fecal sludge at high temperatures, the pathogens are 100% eliminated. Hence, in all three cases, hygiene criteria can be marked as very good.

When it comes to odor emission, odor-causing agents in human solid waste are hydrogen sulfide, methyl sulfide, methanethiol, dimethyl disulfide, dimethyl trisulfide (Ward, B.J 2014). Sol-char toilet model has poor performance because it does not include the odor elimination feature in the pyrolysis process, therefore, the operating the reactor will cause smell and odor nuisance. On the other hand, the design of a biochar reactor in Kenya is not as complexed and complete like the close process in the Greenlife pyrolysis plant, however, it still eliminates the odor well with three odor elimination features: charcoal filter, lean burn combustion to treat the odor-causing syngas and sub-atmospheric pressure to draw air in that deserves a good mark. And with the most automated and complete function unit, the Greenlife pyrolysis plant possesses a very good mark.

Sustainability becomes an essential trend for future development to reserve resources, energy recovery and to protect the environment. Sol-char toilet design is an innovative solution to capture the sunlight and only use solar renewable energy to power the pyrolysis process, it is a sustainable strategy to take the advantages of the clean and free solar energy for the to operate pyrolysis model without electricity and other kinds of energy input, especially a good way for the poor infrastructure and energy shortage conditions in the developing countries. The two other models also have its way to recover its energy output through the combustion of the byproduct syngas to fuel back as a thermal source for the pyrolysis reactor. The biochar reactor biochar utilizes natural gas and biochar as other supplemental sources for energy put while Greenlife plant uses electrical power input. Even though the Sol-char system does not require additional energy input sources, it does not have the feature to handle the syngas resulting from the pyrolysis process, therefore, the exhaust including CO_2, CO may release to the environment and add to the severity of global warming effect. Greenlife pyrolysis plant at the industrial scale handles very well the syngas, not only recovers its thermal energy but also treats the exhaust appropriately before releasing it into the environment and the design is even awarded a climate protection prize. As for the biochar reactor, the complete combustion of syngas resulting in additional CO_2 emission plus the CO_2 emitted itself from the pyrolysis process that needs to be considered. This is the reason why the biochar reactor has the lowest sustainability mark compared with other the two.

Considering the effectiveness of pyrolysis technologies, Sol-char toilet design and biochar reactor model in Kenya have the same advantage of operating without grid energy, water, or sewage infrastructure that is very beneficial to the developing countries' conditions. In addition, their model design is also easy to assemble and maintain using commonly available hand tools, find materials available locally and to scale. However, their operation efficiency can not be compared with the industrial pyrolysis plant. The Sol-char toilet model does not have the pre-drying compartment that lowers the efficiency of the pyrolysis process a lot to treat the high moisture content fecal sludge. Besides, the energy input will be hard to control because it depends on the varied weather condition and solar radiant, therefore, the model can not function fully, especially at night when there is no thermal source for the pyrolysis process to take place. The small-scale bio-char reactor can be considered as a good efficient design since it has a quite comprehensive operation from pre-drying, pyrolyzer, combuster to burn syngas and heat exchanger for heat recovery, the operation does not depend on other external factors except the heating value and moisture content of input fecal sludge (optimum values of 20-22 MJ/kg and 60% moisture). With the high automation, remote control and completion of the industrial pyrolysis model, Greenlife plant possesses the better function that can handle the limitation of larger than 6 MJ/kg heating value of fecal sludge input and varier moisture content that is more feasible to treat fecal sludge in specific and sewage sludge in general.

Cost is an indispensable element when considering economic efficiency. The overall cost for the Sol-char toilet is 3500 USD for this household model (Sol-char sanitation). That is quite expensive, especially to be applied in the developing countries where its operational benefit should be. In contrast, the biochar revenue from Sol-char toilet ranges from $0.05 to $0.09/user/day (Sol-char sanitation). Therefore, the model does not have so much economic efficiency and better be used as a sanitation solution to safely handle fecal sludge. This situation is improved with the case for biochar reactor in Kenya since the project handling a whole community fecal sludge gathering together and found a local partner for their output. Even though the production cost and not published, the authors wrote in their report that the cost should be minimized. That is also the same case for the Greenlife pyrolysis plant, with the larger population handling, the economic benefit will be clearer and the biochar product can be commercialized. However, the production cost usually overlaps that benefit and it will require long-term investment to be profitable.

5 DISCUSSION AND CONCLUSION

In conclusion, these three cases with different pyrolysis scales and technologies have both pros and cons. However, through the literature review of the three cases in specific and the pyrolysis fecal sludge in general, pyrolysis technology has proved to be feasible as a sanitation solution for fecal sludge treatment and potential energy recovery via biochar and syngas production. To better understand the challenges and opportunities for pyrolysis in fecal sludge treatment to progress from the strength and minimize the weakness for the future developed, a SWOT analysis is conducted and its results are presented in Figure 12.

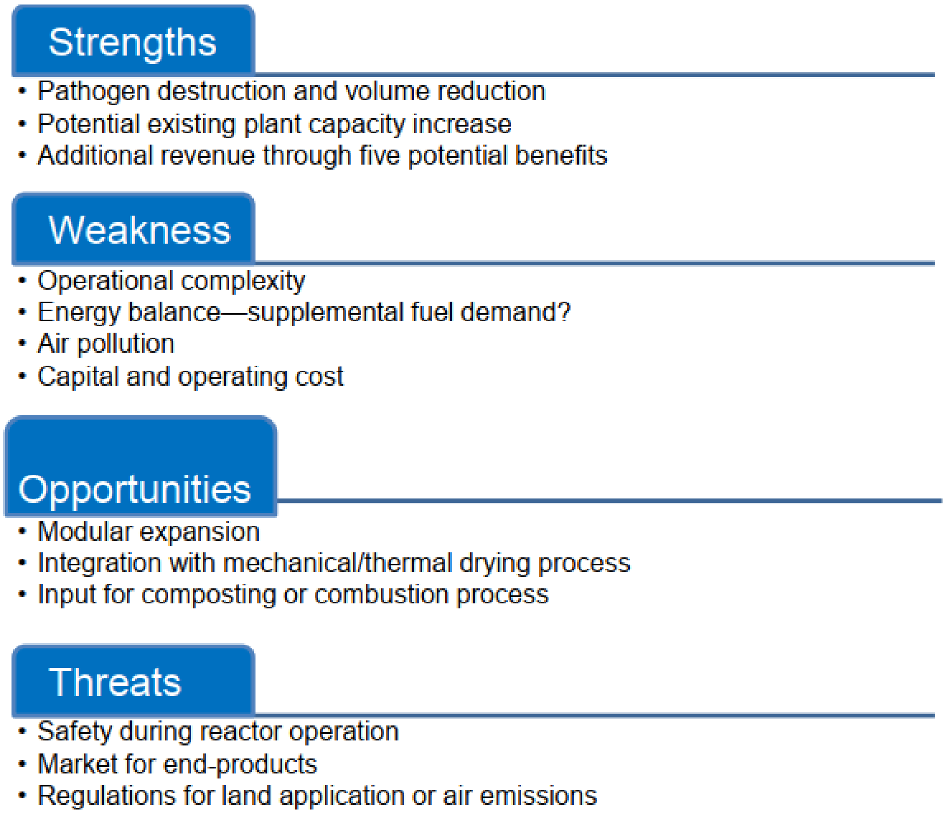


FIGURE 12. SWOT analysis results of pyrolysis for fecal sludge management in low-income countries (Cunningham et al. 2016)

Considering strength, biochar production resulted from the pyrolysis process has five potential benefits which are briefly illustrated in Figure 13. The first advantage of fecal sludge pyrolysis can be sustainable waste management, emphasizing on pathogen destruction. Moreover, the benefits of biochar formed solid fuel and soil enhancement would provide income sources through fuel and soil amendment sales. Finally, carbon sequestration and pollutant immobilization are added value. (Cunningham et al. 2016)

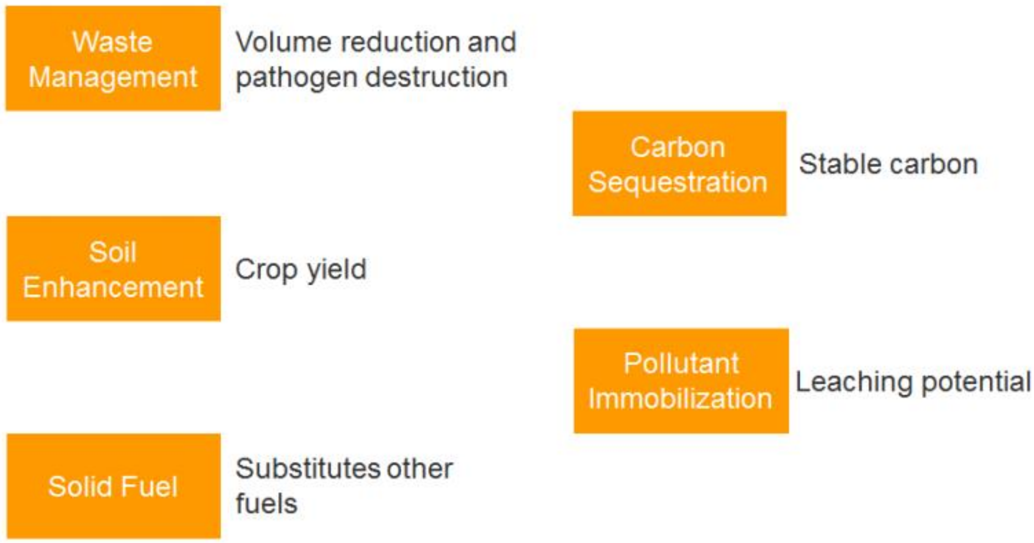


Figure 13. Five potential benefits of char production in the context of fecal sludge management (Jeffrey & Bezemer et al. 2015).

Weaknesses of fecal sludge pyrolysis are process complexity, possible air pollution from burning pyrolysis syngas, and potential supplemental fuel requirements like in the biochar reactor in Kenya or even the large-scale Greenlife pyrolysis plant. Fulfilling the energy demand needed to heat the fecal sludge will depend on its characteristics, energy content, dry matter content, and reactor heat demand. In the case where pyrolysis gas cannot meet the reactor heat demand, supplemental fuel would need to be combusted. (Cunningham et al. 2016)

Opportunities for fecal sludge pyrolysis include modular scale, integration with mechanical dewatering/thermal drying, and alternative markets for biochar beyond the five potential benefits listed above. Besides, there is also the opportunity to use char as input for co-processing other types of organic waste in composting or co-combustion process (Cunningham et al. 2016)

Potential significant threats of fecal sludge pyrolysis are the safety issues during pyrolysis exhaust management and feedstock or biochar collection and handling. Developing a market for the fecal sludge byproducts is also a challenging but viable task that will heavily influence fecal sludge pyrolysis financial beneficiary to draw investment. Another possible threat is that fecal sludge char as a soil amendment could prove ineffective for certain char, soil, environmental condition, and crop combinations. In addition, the biochar may have to pass complex regulation control for a product derived from fecal matters or even can not meet the requirement in some countries. (Cunningham et al. 2016)

Overall, more research and experiments need to be conducted for further improvement in pyrolysis treatment for fecal sludge from small to large scale, especially for sustainable renewable energy powering pyrolysis processes like the innovative Sol-char toilet model. Future experimental works conducted out under closely controlled operating conditions will provide a better understanding of the potential of fecal sludge pyrolysis to safely and cost-effectively determine the technical feasibility and financial resource requirement of implementing pyrolysis as a fecal sludge treatment process which results in the most efficient operation and beneficial byproducts.

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