Technologies for Energy Recovery from Faecal Waste

Technical and Financial Analysis – Pyrolysis

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BILL & MELINDA GATES foundation

EVI Sustainable Solutions for the Environment

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Abbreviations and Acronyms:

CSR	Corporate Social Responsibility
DS	Dry Solid
FS	Faecal Sludge
FsDF	FS Derived Fuel
HTC	Hydro-Thermal Carbonization
INR	Indian Rupee
IRR	Internal Rate of Return
IT	Income Tax
kW	Kilo Watt
Liq	Liquid
MNRE	Ministry of New and Renewable Energy
MTV	Mobile Toilet Van
NPV	Net Present Value
O&M	Operation and Maintenance
P&M	Plant and Machinery
PBDIT	Profit Before Depreciation Interest and Tax
PBIT	Profit Before Interest and Tax
PBT	Profit Before Tax
PLF	Plant Load Factor
Q1	Quarter 1 (April-June)
Q2	Quarter 1 (July-September)
Q3	Quarter 1 (October-December)
Q4	Quarter 1 (January - March)
RRS	Resource Recycling System
SFC	Specific Fuel Consumption
SLM	Straight Line Method
WWT	Waste Water Treatment

About the Author

This report is created under the Bill and Melinda Gates Foundation's Water, Sanitation, and Hygeine ("WSH") initiative. The work strives to inform future WSH opportunities aiming to improve faecal sludge management on technical and financial feasibility of resource recovery efforts under different scenarios in Indian Cities. However the context of the work is global and models presented here can be customized to suit local conditions.

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About EVI

Founded in 1999, Emergent Ventures was established with the twin goal to accelerate action against climate change and to foster sustainable development. EVI works with the governments, government supported institutions, international development organizations and industries in public and private sector to deliver consultancy services across the full spectrum of sustainable development issues.

EVI's team comprises of professionals from technology, finance, policy and strategy areas with expertise and experience in energy & climate policy, corporate sustainability, carbon markets, sustainable transportation, waste management, and renewable energy (wind, solar, biomass). With a mix of market understanding, sectoral expertise and innovative analytics, it works throughout the life cycle of programs.

EVI is currently working on over 300 diverse projects across geographies in Asia (India, Srilanka, Bangladesh, Pakistan, Singapore, Malaysia, Thailand, Indonesia, Philippines, Nepal, Bhutan), Africa (Nigeria, Egypt, Algeria), Americas (USA, Mexico) and Europe. EVI clients include governments, UN Organizations, international donor agencies, NGOs and corporate. EVI covers sectors - Oil & Gas, Utility, Cement, Steel, Textile, Fertilizer, Pharmaceutical, Hospitality, Aviation, Financial, Food & Beverage among others including companies in fortune 500 list. EVI is considered thought leader in its domain of work.

Summary

This is a technical cum financial analysis report on the use of FS for energy recovery purpose. Out of the five technology areas planned for the study namely Gasification, Hydrothermal Carbonization, Pyrolysis, Fermentation and Anaerobic Digestion, Pyrolysis has been evaluated in this part of the study. The technology has been evaluated on its suitability to use FS for resource recovery and financial viability. The analysis also provides a plug and play tool to project developers to calculate the Levelized cost of bio-oil in different scenarios. The bio-oil would be used for energy recovery in suitable system e.g. as engine fuel. Following is the construct of the report.

Chapter 1: Technology Analysis provides details of the technology under consideration, process description and its raw feed requirement. It also focuses on suitability of FS as raw feed and its pre-processing requirement so that FS can be used for production of bio-oil comparable to industrial diesel.

Chapter 2: Financial Analysis provides the Levelized cost of Bio-oil fuel produced by using Pyrolysis process under various scenarios of FS procurement. The financial performance has been evaluated for following FS procurement models:-

Model 1 - FS Collection using Mobile Toilet Vans

Model 2 - FS Collection and transportation - with own infrastructure

Model 3 - FS Collection and transportation - outsourced

The Levelized cost of bio-fuel can be compared with the fuel it would replace for energy recovery. For example, if bio-oil is used in diesel engines, its cost can be compared with that of diesel to see whether it is a viable proposition. The price of bio-oil can also be fixed based on the fuel it would replace to see whether it is a viable venture for a bio-oil producer.

Chapter 3: Conclusion discusses the results and presents the challenges in the areas of technology and financial viability of the project. As per the analysis, the cost of bio-oil using FS sourced from MTVs is the lowest however it entails higher upfront capital requirement in infrastructure.

Chapter 4: Limitation provides the limitation in terms of technology and financial viability of the process.

1. *Technology Analysis*

1.1. Technology Description

Pyrolysis is the thermal decomposition of FS into liquids, gases, and char (solid residue) in the complete absence of oxygen. Pyrolytic products can be used as fuels or be utilized as feedstock for chemical or material industries. Materials suitable for Pyrolysis processing are coal, animal and human waste, food waste, paper, cardboard, plastics, rubber and biomass.

The basic process of producing bio-oil using FsDF is illustrated as below:

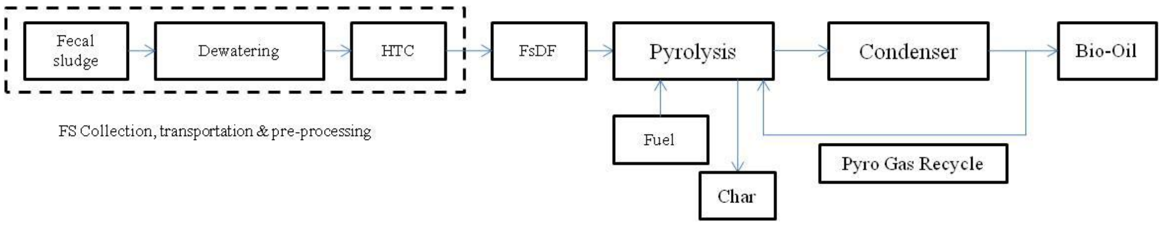

FIGURE 1: BASIC SCHEMATIC OF PYROLYSIS PROCESS

There could be various other options to produce FsDF fuel from faecal sludge. However in the present report, the FsDF fuel produced by using hydrothermal carbonization of Faecal sludge has been considered for Pyrolysis.

1.1.1. Types of Pyrolysis Technology

There are three primary types of pyrolytic reaction, which are differentiated by the temperature and the processing or the residence time of the feed stock.

TABLE 1: COMPARISON OF PYROLYSIS PROCESSES[1]

Pyrolysis type	Slow Pyrolysis	Flash Pyrolysis	Fast Pyrolysis
Temperature, ^{0}C	350 – 400	350 – 450	450 – 550
Time	2 – 30 min	4 min	1 – 5 sec
Yields, % wt on dry basis			
Char (%)	2 – 60	19 – 73	0 – 50
Liquid (%)	0 – 60	18 – 60	10 - 80
Gas (%)	0 – 60	9 – 32	5 - 60
Heating rate, ^{0}C/sec	0.1 - 2	>2	200- 10^5
Advantages	• Operation cost is low as compared to fast Pyrolysis. • Operation and	• Operation cost is low as compared to fast Pyrolysis. • Operation and	• High bio oil yield compared to slow and flash Pyrolysis. • Pre-shorting of

[1] Peter Alexander Brownsort, Biomass Pyrolysis processes: Performance parameters and their influence on Bio char system benefits, Table 1, page 22.

	maintenance is easy.	maintenance is easy.	feed stock is not required. Particle size of 2-6 mm is preferable.
Disadvantages	• In this process fuel must be pre-sorted and processed to <6 mm (1 to 2 mm. preferred). • Less bio-oil yield.	• Compared to slow Pyrolysis, considerably less tar and gas are produced. • Pre shorting of feed stock required.	• Capital cost is high compared to slow and plash Pyrolysis. • O&M cost is relatively higher too.

Based on above assessment it is clear that Fast Pyrolysis will result in high bio-oil yield and it is currently the most widely used Pyrolysis system[2]. For further analysis, only Fast Pyrolysis process has been considered.

1.1.2. Pyrolysis Products

Fast Pyrolysis mainly produces three products bio oil, char and pyro gas.

1) **Bio Oil:** If Fecal sludge[3] is used as raw feed at 8-10 % moisture in fast Pyrolysis, the bio oil yield of 23.43 % (wt %) and energy content of approx 27.30 MJ/kg can be achieved.

As a clean fuel, bio oil has a number of advantages including the following:

- It is renewable and locally produced from organic waste.
- It can be stored and transported similarly to petroleum-based products.
- It is a greenhouse gas neutral and can generate carbon dioxide credits.
- It generates lower NOx emission than light fuel oil in gas turbines and diesel fuel in stationary diesel engines.

Subsequently, high temperature, rapid heating rate, and low vapour partial pressure will promote the formation of bio-oil. For the production of bio oil, the reactions must be interrupted by rapid quenching of intermediates before equilibrium is reached.

2) **Pyro Gas:** The gas product is typically a mixture of carbon dioxide (9-55% by volume), carbon monoxide (16-51%), hydrogen (2-43%), methane (4-11%) and small amounts of higher hydrocarbons. Through technology advancement in fast Pyrolysis process, fuel consumption can be reduced by recycling the pyro gas after condensation.

3) **Char:** The devolatalization of biomass during pyrolytic reactions yields a solid residue (char). Increasing the heat treatment temperature reduces char yield and also increases the aromatization of char as measured by the aromatic carbon content of the acids.

[2] http://www.altenergymag.com/emagazine.php?issue_number=09.02.01&article=pyrolysis#.UXUCF6Kmh1A

[3] The bio oil yield from FS is not known. Hence the bio-oil yield from FS has been assumed similar to the bio-oil yield from Pyrolysis of chicken litter.

Independently, bio-char can increase soil fertility, increase agriculture productivity and provide protection against some foliar and soil borne diseases.

1.2. Raw Feed Characteristics

1.2.1. Feed Stock Requirement for Pyrolysis

Following are the raw feed requirement for fast Pyrolysis process:-

1) **Moisture content:** Fast Pyrolysis processes in general require fairly dry feed, around 10% moisture, so that the rate of temperature rise is not restricted by evaporation of water.

2) **Particle size:** Feed particle size can significantly affect the balance between char and liquid yields. Larger particle sizes tend to give more char. Feed stock is then ground to 2-6 mm particle size to yield sufficiently small particles, ensuring rapid reaction in the Pyrolysis reactor.

3) **Chlorine content:** The presence of organic chlorine at high temperature (> 250 degC) will result in formation of Dioxin, a toxic gas, which has negative impact on the health. Hence the exhaust should be treated before releasing to atmosphere.

1.2.2. Characteristics of Available FS

FS has certain characteristics, like moisture content, quite different from those of normal Pyrolysis feedstock. It will therefore have to be pre-processed to make it suitable for feeding to the fast Pyrolysis reactor. The requirements of pre-processing and associated challenges will vary according to the source of FS. At present following sources have been identified for study:-

1) FS collected from septic tanks (septage)

2) FS collected from mobile toilet vans (MTV)

1) FS collected from septic tanks

Moisture: FS collected from septic tanks is high on water content. The water content of FS sourced from septic toilets is as high as around 96%. Therefore this will need to be reduced to requirements of the HTC system (below 80% for further drying in reactor). This can be done by dewatering free water from FS.

Particle size: The available FS is in slurry form and not in particle form. Hence this needs to be converted into suitable particle form before Pyrolysis.

Chlorine content: The chlorine content of fecal sludge is very less unless it's mixed with plastic components like bottle etc during handling. This should be avoided.

2) FS collected from Mobile Toilet Vans (MTV)

Moisture: A ten seat MTV has got 2000 liter[4] of storage capacity and on an average 500 people use this on daily basis. It is also found that per person water usage is normally 4 liter per use. Hence FS sludge from MTV of carrying capacity of 2000 liter should be discharged on daily basis in order to maintain the hygiene and cleanliness. The discharge frequency of

[4] http://trade.indiamart.com/details.mp?offer=3952505291

MTV largely depends on water quantity used by individual users[5]. The average value of per person per day excreta generation is 250 gm. Normally, feces are made up of 75 percent water and 25 percent solid matter[6]. Hence the moisture content from the MTV can be estimated as below:-

MTV carrying capacity = 2000 liter per MTV

Average number of Daily usage = 500 person per day

Per person excreta generation = 250 gm per day

Per person solid excreta generation = 250*25% = 62.5 gm per day

Total FS (solid) generation (Daily) = 500 * 62.5/1000 = 31.25 kg per day

Hence, total solid content = 31.25/2000 = 1.56% (approximately 2%)

Hence the moisture content in MTV sludge is approximately 98%. It is similar to water content when compared to septic tanks therefore this need to be reduced to requirements of the HTC system (below 80% for further drying in reactor).

Particle size: The available FS is in slurry form and not in particle form. Hence this needs to be converted into suitable particle form before Pyrolysis.

Chlorine content: The chlorine content of fecal sludge is very less unless it's mixed with plastic components like bottle etc during handling. The chances of this are higher in MTV where users may flush pouch of tobacco (gutkhas[7]) in toilet. This should be avoided or removed before fuel conversion process.

1.2.3. Gap Analysis

The main gap between what is available as-is and what is needed for fast Pyrolysis of FS is excess moisture content, particle size and Chlorine content. Therefore, FS needs to be dewatered and grind before it is considered suitable for fast Pyrolysis process. Following presents the gap between as-is and the fast Pyrolysis requirements in general.

TABLE 2: GAP ANALYSIS OF CHARACTERISTICS

Characteristics	Requirements of Pyrolysis reactor	From Septic Tank (As-is-FS)	From MTV (As-is-FS)
Moisture	<10%	96-98 %	97-98%
Chlorine content	Less	Less	Less

[5] Based on discussion with Prof P. K. Jha, working as an expert for evaluating proposals submitted to the Ministry of New &Renewable Energy, Government of India in the field of biogas and solid wastes management sectors

[6] http://www.britannica.com/EBchecked/topic/203293/feces, EAI Estimates

[7] http://en.wikipedia.org/wiki/Gutka

Particle Size	2-6 mm	Slurry form	Slurry form

In the following section, a detailed discussion is presented on the methods of processing of as-is FS.

1.3. Pre-processing of FS

The major issue is excess moisture content in FS available from septic tank or MTV. This excess water need to be dewatered before further processing in HTC reactor.

Following steps are envisaged for the water reduction purpose:

Step 1: Thickening/Sedimentation

Thickening is carried out in a sedimentation tank or in a sedimentation pond (if adequate land area is available). Water can be removed from top, leaving sludge with 95% water content[8].

Step 2: Dewatering

Dewatering reduces the water content further so that the solids content of the sludge is about 20%[9].

Synapse has identified three potential low-tech systems for dewatering of excess water. All of these systems are capable of producing concentrated solids with a TS of 10%-15% and can take input sludge that contains TSS between 1% and 5% (solid content in septic sludge is less 5%). These three systems are

a) FCK-315 Rotary Thickener,

b) Integrated Engineers CFU-20 belt thickener, and

c) FloTrend Polymate and Sludgemate gravity dewatering box.

As per Synapse, the FCK-315 system provides the best performance in terms of cost. It is also the most compact system and could easily fit onto a small trailer. For these reasons, the FCK-315 rotary thickener has been selected for dewatering purpose.

Step 3: Chlorine

The chlorine content in FS is low however the presence of foreign particles such as plastic material may result in Dioxin formation at high temperature heating. Hence this should be removed before HTC treatment.

[8] http://www.unep.or.jp/ietc/publications/freshwater/sb_summary/11.asp
[9] http://www.unep.or.jp/ietc/publications/freshwater/sb_summary/11.asp

Step 4: HTC treatment

Through HTC treatment of FS, its moisture content reduces below 10% and its particle size also reduces less than 6 mm.

1.3.1. Characteristics of Processed FS

Moisture content: The moisture content of FS after hydrothermal treatment will be less than 10%.

Chlorine content: The chlorine content in FS is low after removal of any foreign particles such as plastic.

Particle Size: Particle size will be less than 6 mm.

Characteristics of FS after pre-processing are given below:

TABLE 3: CHARACTERISTICS OF FS

Characteristics	FS after pre-treatment
Moisture content	<10%
Chlorine content	Lower
Particle Size	<6 mm

1.4. Challenges

1.4.1. Challenges in Pre-processing of FS

Collection and transportation

The key challenge in pre-processing of FS is to collect, transport and take it to the processing facility. Large quantities of water present in the septage make the job even more difficult. The presence of water also puts pressure on the economics of the process as such quantities would mean good money is spent on the transport part in the form of capital investments and also during operation and maintenance of the fleet.

The solution to this problem is to have in-situ treatment solutions where treated waste water is good for use i.e. landscaping, construction activities etc. However this means that users of treated waste water are available in close neighborhood and immediately avoiding need to transport water to a facility for storage. Whether or not this choice is available would impact the economics of the project significantly.

High moisture content

Another challenge is related to dewatering of sludge. If natural drying is used then huge parcels of land will be needed. The thermal drying process is more energy intensive, which will adversely affect economics of the plant.

Dioxin Production

Dioxins are produced at 250-600 degC, hence the exhaust from Pyrolysis reactor, where heating temperature is around 500 degC, should be treated before releasing this to atmosphere.

Other Challenges

Labor: Availability of local labor to operate a facility processing fecal sludge might pose an issue due to psychological or socio-cultural reasons.

Storage: For a facility to operate without breaks, storage capacity for FsDF will need to be maintained on site for a contingency situation. Storage might pose a problem due to the large volume required.

Availability & collection: Availability of FS might be an issue in areas where an on-site storage facility such as septic tank is not present.

Not a proven technology at commercial scale: The Pyrolysis process has been successfully used for Pyrolysis of tyres or plastics however the same technology has not been tested on FS and implemented at commercial scale for processing of FS. Hence the viability of Pyrolysis technology with FS as feedstock is still uncertain.

1.4.2. Challenges in Pyrolysis of FS

There is no proven operational data on the use of FS as raw feed in Fast Pyrolysis process. However there are some publications which recommend the fast Pyrolysis of chicken litter and the composition of chicken litter and FS somehow similar. But this is still a matter of further research.

Temperature

The yield of volatile products (gases and liquids) increases with increasing heating rate and temperature while solid residue decreases. The time required to obtain a certain conversion level decreases with increasing temperature. An increase in Pyrolysis temperature increases the yield of gaseous products and this increases the bio-oil yield after condensation of gas.

Pressure

Pressure has a significant influence on Pyrolysis of biomass. Higher pressure increases the residence time of the volatiles in the reaction zone, resulting in increased yield of low molecular weight gas and decreased tar and liquid products due to cracking reactions. At low pressures, and hence short residence times, tar molecules and heavy liquid products will escape before undergoing further decomposition. This will result in lower formation of gaseous product and hence decrease in bio-oil yield. Hence the operating pressure should be high for maximum bio-oil yield.

Gas Flow rate

Gas flow rate through the reactor affects the contact time between primary vapour and hot char and so affects the degree of secondary char formation. Low flows favor char yield and are preferred for slow Pyrolysis; high gas flows are used in fast Pyrolysis, effectively stripping off the vapors as soon as they are formed.

Bio Oil Instability

Bio-oil is relatively unstable compared to fossil fuels. This is primarily due to slow chemical reactions that produce more polymeric compounds, which gradually increases the molecular weight average of the Pyrolysis liquids and consequently the liquid viscosity. Various reactions between the components of the Pyrolysis liquids and with the storage environment can occur. This can affect the quality of bio-oil over a period of time.

Moisture content

Presence of moisture (greater than 15-20%) in feedstock may lead to higher moisture content in bio-oil and this may lead to phase separation in bio-oil over a period of time. The Pyrolysis liquids are also highly corrosive due to the presence of organic acids derived from feedstock.

2. Financial Analysis

2.1. Description of Plug & Play Excel Model

The plug and play model has been prepared for calculation of Levelized cost of Bio-oil produced from Pyrolysis of FsDF. HTC has been considered for the FS to fuel conversion technology. There are other technologies/ processes however that can be employed for such conversion. The FsDF fuel produced from HTC technology would be used as feed stock in the Pyrolysis system. The analysis has been done for 20 years of lifetime of Pyrolysis system.

The Pyrolysis process has been successfully used for Pyrolysis of tyres or plastics globally however the same technology has not been tested and implemented at commercial scale for the processing of FS. Hence in the present analysis, it has been assumed that the costs (capital cost, fuel cost, O&M cost etc) related to Pyrolysis of FsDF are similar to the costs given for Pyrolysis of tyres. This information has been obtained from FAB India[10], a supplier for Pyrolysis systems for Pyrolysis of tyres. The viability of this technology with FsDF is not yet tested and verified.

In the present analysis, the bio-oil yield has been assumed similar to the yield resulting from chicken litter as raw feed. However this is yet to be tested and verified.

2.2. Various Models for FS procurement

Sustainable FS procurement is critical to the success of the program. Three types of FS procurement models have been considered. The key aspects of FS procurement models are FS collection and transportation from FS sources, its pre-processing and conversion into ready-to-use fuel. Each model presents different scenario of capital expenditure requirement, need of man power, revenue and operating cost streams. These are explained below:

1) **Procurement from septic tanks using own infrastructure: -** In India 38% of urban households have septic tanks. This number of septic tanks is expected to grow steeply in the next few years, but there is no separate policy or regulation for septage management in India at present[11]. Hence septic tanks have been considered as one of the source for FS procurement. Further the collection of FS by using own tankers is financially viable compared to the FS collection from third party septic tank emptier. Hence the same has been considered in this FS procurement model. In this model, the financial return could be maximize by outsourcing tankers for other activities like transportation of waste water, sewage etc.

2) **Procurement from MTV: -** In urban India, approximately 17% people lives in slums[12], where they don't have proper access to sanitation. In that case, mobile toilet vans along with community based toilets could be the based feasible option. Deployment of MTVs in the slum areas will provide access to fresh human excreta.

3) **FS Collection and transportation – outsourced:-** In this model, FS will be procured from third party septic tank emptier. Emptier will sell the FS emptied from household septic tanks to project developer. Project developer doesn't own the infrastructure required for FS collection and transportation. Project developer however processes FS procured from emptier to convert into fuel grade in-house.

The base model has been prepared for five tonne of Pyrolysis reactor.

[10] http://www.wastetyreplant.com/aboutus.php
[11] http://www.urbanindia.nic.in/programme/uwss/Advisory_SMUI.pdf
[12] http://articles.timesofindia.indiatimes.com/2013-03-22/india/37936264_1_slum-population-slum-households-rajiv-awas-yojana

Figure 2 below shows the basic model of Bio-oil production under various FS procurement sources. The key steps have been delineated to demonstrate the source of FS, production of FsDF and production of bio-oil in the Pyrolysis system. There could be various other options to produce fuel from Faecal sludge. However in the present report, the fuel produced by using hydrothermal carbonization (HTC) process has been considered for Pyrolysis.

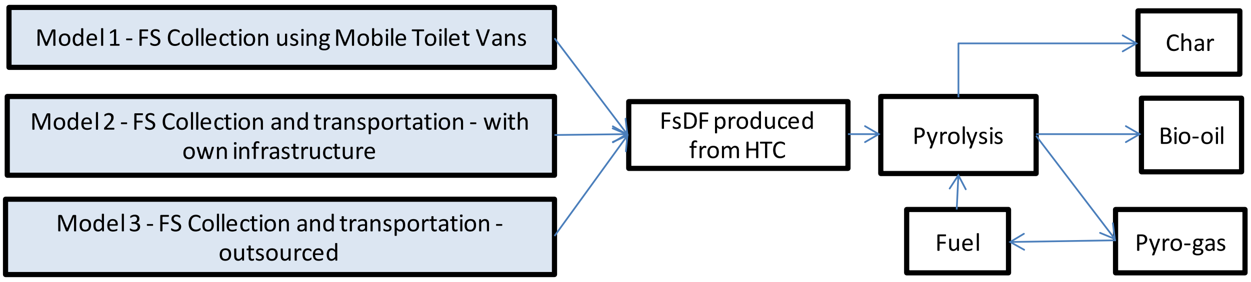

FIGURE 2: PROCESS FLOW DIAGRAM FOR PYROLYSIS PROCESS

The pros and cons for each FS procurement method have been provided in the table below.

TABLE 4: FS PROCUREMENT MODELS - PROS AND CONS

Index	Assumptions	Pros	Cons
Model 1	MTVs will be deployed by project developer at various locations in the city for people who don't have direct access to any formal sanitation system. The FS collected from MTV will be transported to the HTC plant for further processing before its conversion to bio-oil using Pyrolysis process.	• Access to fresh FS and hence high carbon content and good energy potential present. • Supply of FS will be consistent with high FS solid content.	• Handling of FS will be a challenge due to its form, odor, presence of pathogens and distributed nature of its availability. • Scaling up FS availability would be difficult. • Higher capital costs due to procurement of MTVs and high variable cost associated with operation and maintenance of MTV. • MTV model has not been very successful in many cities. This is mainly due to poor maintenance of MTVs. Hence the cost of maintenance will be high for proper functioning and mass acceptability of MTVs.

Model 2	In this model, FS will be procured directly from septic tanks owner by project developer. In this case, the emptying, collection and transportation network is owned and run by project developer.	• Emptying of FS from septic tanks generate revenue for the project developer. • Project developer can share the tanker service with other business like Sewer sludge transportation, waste water transportation etc to maximize the return.	• Higher capital costs due to procurement of emptying tankers and high variable cost associated with operation and maintenance of emptying system. • The project profitability or loss from collection and transportation also impacts the overall cost of FsDF production.
Model 3	In this model, FS will be procured from third party septic tank emptier. Emptier will sell the FS emptied from household septic tanks to project developer. Project developer doesn't own the infrastructure required for FS collection and transportation. Project developer however processes FS procured from emptier to convert into fuel grade in-house.	• The capital cost is reduced due to no investment in collection, transportation and storage infrastructure. • Direct fixed cost of man power engagement and running the collection and transportation system avoided. Project developer doesn't have to deal with individual household septic tank owners.	• Project developer pays for the emptier's service. • Project developer will not have access to the potential revenue from septic tank emptying from households. Supply of FS may not be consistent as this depends on third party supplier.

The levelized cost of Bio-oil has been calculated for a period of 20 years, similar to plant lifetime of Pyrolysis system. Following costs and revenue streams are considered for estimation of Bio-oil cost.

TABLE 5: KEY COST FACTORS FOR HTC

Particulars	Model 1	Model 2	Model 3
Capital cost of MTV	√	X	X
Capital cost for truck	X	√	X
Capital cost for WWT plant	√	√	√
Capital cost of dewatering system	√	√	√

Capital cost for drying system	√	√	√
Land cost	√	√	√
O&M cost of truck	X	√	X
O&M cost of MTV	√	X	X
O&M cost of WWT	√	√	√
O&M cost of dewatering system	√	√	√
O&M cost of drying	√	√	√
Cost of transportation from sanitation site to plant site	√	√	X
Cost of transportation of treated waste water	√	√	√
Procurement cost of FS sludge from third party	X	X	√

TABLE 6: KEY COST FACTORS FOR PYROLYSIS

Particulars	Model 1,2 & 3
Capital cost of Pyrolysis system	√
Cost for FsDF	√
Land cost	√
O&M cost of Pyrolysis reactor	√
Power cost & Labor cost	√
Fuel (coal) cost	√

The FsDF cost has been taken from HTC model for the given source of FS.

2.3. Sources of Revenue

TABLE 7: SOURCES OF REVENUE FOR VARIOUS FS PROCUREMENT MODELS

SN	Revenue Source	Process	Model 1	Model 2	Model 3
1	Revenue from septic tank emptying	HTC	X	√	X
2	Revenue from per person toilet usage of MTV	HTC	√	X	X
3	Revenue from sale of treated waste water	HTC	√	√	√

4	Revenue from sale of Char	Pyrolysis	√	√	√

2.4. Capital Cost

2.4.1. HTC System

In the present case the project cost has been referred to for a typical 5 tonne HTC system. The need for other infrastructure has been identified accordingly. The breakup of capital cost has been provided below for all FS procurement models:-

TABLE 8: CAPITAL COST FOR MODEL 1- FS COLLECTION USING MOBILE TOILET VANS

Parameters	Unit	Value	Reference
Capital cost for one MTV	USD	7,407	Based on information provided by third party
Total capital cost for MTVs	USD	185,185	Calculated
Capital cost of dewatering system	USD	15,000	FCK-315, Rotary thickener Synapse. The cost has been taken when volume is high.
Capital cost for WWT plant	USD	18,519	For 50KLD system - http://www.cseindia.org/node/3770
Capital cost of RRS technology (HTC)	USD	25,000	Cost provided by Prof Yoshikawa, Tokyo Institute of Technology, for RRS technology
Land cost	USD	5,400	Land cost might change significantly for specific scenarios
Total Cost	USD	**249,104**	**Calculated**

TABLE 9: CAPITAL COST FOR MODEL 2- FS COLLECTION AND TRANSPORTATION - WITH OWN INFRASTRUCTURE

Parameters	Unit	Value	Reference
Capital cost for one truck	USD	31,481	Based on report published by IRC, Bangalore
Number of trucks required	Number	2	Refer to the plug and play model for calculation
Total capital cost for trucks	USD	62,963	Calculated
Capital cost of dewatering system	USD	15,000	FCK-315, Rotary thickener Synapse. The cost has been taken when volume is high.
Capital cost for WWT plant	USD	18,519	For 50KLD system - http://www.cseindia.org/node/3770
Capital cost of RRS technology (HTC)	USD	25,000	Cost provided by Prof Yoshikawa, Tokyo Institute of Technology, for RRS technology
Land cost	USD	5,400	Land cost might change significantly for specific scenarios
Total Cost	**USD**	**126,881**	**Calculated**

TABLE 10: CAPITAL COST FOR MODEL 3- FS COLLECTION AND TRANSPORTATION - OUTSOURCED

Parameters	Unit	Value	Reference
Capital cost of dewatering system	USD	15,000	FCK-315, Rotary thickener Synapse. The cost has been taken when volume is high.
Capital cost for WWT plant	USD	18,519	For 50KLD system - http://www.cseindia.org/node/3770
Capital cost of RRS technology (HTC)	USD	25,000	Cost provided by Prof Yoshikawa, Tokyo Institute of Technology, for RRS technology
Land cost	USD	5,400	Land cost might change significantly for specific scenarios
Total Cost	**USD**	**63,919**	**Calculated**

2.4.2. Pyrolysis System

In the present case the project cost has been referred from a typical 5 tonne Pyrolysis system. The need for other infrastructure has been identified accordingly. The breakup of capital cost has been provided below for all FS procurement models:-

TABLE 11: CAPITAL COST FOR PYROLYSIS SYSTEM

Parameters	Unit	Value	Reference
Capital cost for Pyrolysis reactor	USD	51,852	As per information provided by FAB India for 5 Ton system (FI-RF-5T)
Installation charge	USD	926	
Hydraulic Auto feeder	USD	5,741	
Hydraulic cutter	USD	6,019	
Material handing screw	USD	2,333	
Chimney cost extra 100 feet	USD	4,074	
Land cost	USD	5,400	Land area assumed similar to the area required for gasification system
Total	**USD**	**76,344**	**Calculated**

2.5. Others Input Parameters

The model presents opportunity to change critical input parameters through drop down list. This variation can be used for optimization of this model. Following input factors are subjected to variation in the present plug and play model:

TABLE 12: VARIATION RANGE FOR CRITICAL INPUT PARAMETERS

SN	Input Factor	Base Scenario	Range from	Range To	Interval
1	Power tariff	6 Rs/kWh	4 Rs/kWh	10 Rs/kWh	1 Rs/kWh
2	Debt Equity ratio	70:30	70:30	50:50	-
3	Debt interest rate	12%	10%	15%	1%
4	Discount rate	16%	12%	16%	1%
5	Currency conversion	54 Rs/USD	49 Rs/USD	56 Rs/USD	1 Rs/USD
6	Loan repayment period	6 years	6 years	10 years	1 year

2.6. Results and Discussion

2.6.1. Result and discussion for HTC process

The Levelized cost of fuel has been calculated for three types of FS procurement models. The plug and play model also provides the Levelized cost of fuel for individual processes like collection and transportation, dewatering and RRS system. The revenue streams applicable for all models have also been considered while calculating the Levelized cost of fuel. This will help us to identify the cost intensive process and at the same time it'll help us to take necessary measures to reduce the overall Levelized cost of fuel.

Following revenue streams are considered:

Revenue 1: from septic tank emptying

Revenue 2: from per person toilet usage of MTV

Revenue 3: from sale of treated waste water

Levelized cost FsDF:

The Levelized cost of FsDF has been provided below. This also provides the Levelized cost for individual processes.

TABLE 13: COST OF FS FUEL (USD/KG)

Model	Collection and transportation	Dewatering & WWT	RRS technology	Overall cost
Model 1 - FS Collection using Mobile Toilet Vans	-0.10	0.08	0.09	**0.06**

Model 2 - FS Collection and transportation - with own infrastructure	-0.01	0.08	0.09	**0.16**
Model 3 - FS Collection and transportation - outsourced	0.04	0.08	0.09	**0.21**

As is evident Model 1 is the most viable for production of FsDF. This is mainly because of revenue collection from per person usage of MTV. This cost is also comparable to the cost of other biomass residue available in the region.

A sensitivity analysis of +/-100% on capital cost, O&M cost and Revenue has been performed.

The outcome of the sensitivity analysis has been summarized below for all models:-

For Model 1

1. Variation in project cost has little impact on FsDF cost.
2. Variation in O&M cost has significant impact on FsDF cost
3. FsDF cost is more sensitive to O&M of dewatering system and O&M cost of RRS plant. The annual O&M cost for dewatering system is $81,000 per annum which is much more than its capital cost. This should be reduced.
4. FsDF cost is more sensitive to revenue from MTV usage compared to the revenue generated from sale of treated waste water.

The FsDF cost is zero under following scenarios:

TABLE 14: BREAK EVEN CASE FOR MODEL 1

Case	Dewatering O&M	RRS O&M		Revenue from MTV usage	Revenue from sale of waste water
Unit	**USD/year**	**USD/year**		**USD/person**	**USD/tanker**
Break-even	39,207	14,375		0.05	25.32
Base case	81,000	56,167		0.04	11.1

The possibility of such variation need to be evaluated based on discussion with supplier and market survey.

For Model 2

1. Variation in project cost has little impact on FsDF cost.
2. Variation in O&M cost has significant impact on FsDF cost
3. FsDF cost is more sensitive to O&M of dewatering system and O&M cost of RRS plant. The annual O&M cost for dewatering system is $81,000 per annum which is much more than its capital cost. This should be reduced.

4. FsDF cost is more sensitive to revenue from toilet emptying
5. The FsDF cost is zero when total O&M cost is reduced to 38,943 USD/year. However the possibility of such variation need to be evaluated based on discussion with supplier and market survey.

For Model 3

1. Variation in project cost has little impact on FsDF cost.
2. Variation in O&M cost has significant impact on FsDF cost
3. FsDF cost is more sensitive to O&M of dewatering system and O&M cost of RRS plant. The annual O&M cost for dewatering system is $81,000 per annum which is much more than its capital cost. This should be reduced.
4. In this model there is only one source of revenue i.e. revenue from sale of treated waste water. Any variation in this revenue has significant impact FsDF cost is more sensitive to revenue from toilet emptying
5. The FsDF cost is zero when total O&M cost is reduced to 38,943 USD/year. However the possibility of such variation need to be evaluated based on discussion with supplier and market survey.

Energy ratio has been also calculated to check whether the HTC process is generating net surplus energy or not. The calculation for the same has been provided below.

TABLE 15: ENERGY RATIO (ENERGY-OUT/ENERGY-IN)

Parameter	Value	Unit	Reference
Quantity of HFO used in boiler	180	Litre/day	As per information provided by Prof Yoshikawa, Tokyo Institute of Technology, for RRS technology
Calorific value of HFO	41200	kJ/litre	http://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html
Electricity-Reactor	25	kWh/day	As per information provided by Prof Yoshikawa, Tokyo Institute of Technology, for RRS technology
Electricity-Dehydrator	10	kWh/day	As per information provided by Prof Yoshikawa, Tokyo Institute of Technology, for RRS technology
Energy-in	7542000	kJ/day	Calculated
Quantity of FsDF produced	1000	kg/day	Calculated
Caloric value of FsDF	3000	kcal/kg	Calorific value of FS result from Uganda, Ghana, and Senegal by Teddy Nakato
Energy-output	12560400	kJ/day	
Energy ratio	**1.67**	Ratio	Calculated

Since the energy ratio is more than one hence the HTC process results in net surplus energy generation.

2.6.2. Result and discussion for Pyrolysis process

The Levelized cost of Bio-oil has been calculated for bio-oil produced from FsDF. FsDF is produced by using HTC technology.

Levelized cost Bio-oil:

The Levelized cost of Bio-oil has been provided below. This also provides the Levelized cost for FsDF. This will help to compare the value add to the product after Pyrolysis.

TABLE 16: PRODUCTION COST OF BIO-OIL (USD/LITRE)

Model	Bio-oil Cost (USD/litre)
Model 1 - FS Collection using Mobile Toilet Vans	**0.19**
Model 2 - FS Collection and transportation - with own infrastructure	**0.39**
Model 3 - FS Collection and transportation - outsourced	**0.50**

As is evident Model 1 is the most viable for production of Bio-oil. This is mainly because of lower cost of production of FsDF from model 1. Model 2 and 3 are also viable option at the given market price of diesel. The market price of commercial diesel is $0.83 per liter which is much higher than the Levelized cost of biodiesel production.

A sensitivity analysis of +/-100% on Capital cost, O&M cost, FsDF cost, Char price and Bio-oil yield has been performed.

The outcome of the sensitivity analysis has been summarized below for all FS procurement models:-

For Pyrolysis

1. Variation in capital cost of Pyrolysis plant has little impact on production of bio-oil.
2. Bio-oil production cost is most sensitive to the price of feed stock (FsDF).
3. Bio-oil production cost is also sensitive to O&M cost, char price and bio-oil yield.
4. The probability of such variation in bio-oil yield needs to be evaluated based on selection of suitable Pyrolysis type or by mixing with other types of feed like plastic and tyres to increase bio-oil yield.
5. An appropriate way will be to consider the combined variation in all critical input parameters to reduce the production cost of bio-oil.

3. Conclusion

3.1. Conclusion – HTC process

1. Quality of FsDF: - The calorific value of fuel derived from sewage sludge is approximately 2000 kcal/kg. Since calorific value of FS is better than sewage hence this may result in higher calorific value of FsDF fuel after HTC treatment. However this is yet to be tested on commercial scale. Excess heating or higher holding time may result in poor quality of fuel.

2. The MTV model (Model 1) is the most successful model for hydrothermal carbonization process. However the success of this model depends on the maximum utilization of MTV. This can be assured by providing proper maintenance of MTV vans. A provision of pay and use, similar to public toilet, can be implemented there. However this is yet to be tested.

3. The production cost of FsDF in case of model 1 can be reduced to zero in following conditions:-

Case	Dewatering O&M	RRS O&M		Revenue from MTV usage	Revenue from sale of waste water
Unit	**USD/year**	**USD/year**		**USD/person**	**USD/tanker**
Break-even	39,207	14,375		0.05	25.32
Base case	81,000	56,167		0.04	11.11

   The capacity of dewatering system is 25 GPM or 136 KLD whereas the process requirement is only 45 KLD. Hence the selection of appropriate size of dewatering system may reduce the capital cost and O&M cost of dewatering system by half. In that scenario, it's possible to have zero production cost for FsDF.

4. Characteristics of FS collected from various sources: - The calorific value of FS doesn't change much due to change in source and the age of FS. However the moisture or water content might vary. The HTC technology is appropriate when moisture content is less than 80%. Hence dewatering of surplus water is major challenges when handling with FS.

5. Formation of Dioxin: - Present of chlorine rich material may result in formation of dioxin when heated above 250 dig. Hence the presence of foreign chlorine rich materials (plastic etc) should be removed before hydrothermal carbonization process.

3.2. Conclusion – Pyrolysis process

1. The MTV model (Model 1) is relatively cheaper for production of Bio-oil from Pyrolysis process compared to model 2 & 3. However the success of this model depends on the production cost of FsDF.

2. Fast Pyrolysis is the most appropriate for Pyrolysis of FsDF as this will result in maximum production of Bio-oil.

3. In case of Model 1, the Pyrolysis process adds value to the product hence Pyrolysis of FsDF is recommended for profit maximization. The calculation for the same has been provided below.

   Levelized cost of FsDF = 0.06 USD/kg
   Quantity of FsDF used in Pyrolysis = 1,500,000 kg/year
   Hence, market value = 90,000 USD (assuming the Levelized cost is market price)

   Bio-oil yield = 23%
   Bio-oil production from given quantity of FsDF = 345,000 kg/year
   Bio-oil production from given quantity of FsDF = 386,400 litre
   Levelized cost of bio-oil production = 0.19 USD/Liter
   Market price of bio-oil (assumed similar to diesel) = 0.83 USD/litre

   Value add = 386,400*(0.83-0.19)-1,500,000*0.06 = 157,296 USD/year

   However in case of Model 2 & 3, it's not recommended to go for Pyrolysis process as the value addition is negative. In that case the value addition would be

   Value add = 386,400*(0.83-0.39)-1,500,000*0.16 = (-) 69,984 USD/year
   Value add = 386,400*(0.83-0.50)-1,500,000*0.21 = (-) 187,488 USD/year

4. The production cost of Bio-oil can be reduced to zero by reducing the production cost of FsDF to zero. However this would be a hypothetical scenario. Hence a combination of parameters can be used for reduction of production cost of bio-oil.

5. Formation of Dioxin:- Present of chlorine rich material may result in formation of dioxin when heated above 250 degC. Hence the exhaust gas should be treated before emitted to atmosphere.

6. Availability of FsDF:- To overcome this issue, FsDF can be mixed with other types of waste like tyres, plastic, biomass also. However any mixing with other types of waste need to be tested.

Policy & Regulation

1. Land acquisition is a major problem for waste to energy projects. Hence the government may facilitate and provide the land on lease basis to project promoters in areas nearby urban region to reduce transportation cost.

2. Government may allocate funds for design and development of such waste to energy projects on pilot scale similar to the funding allocated for wind and solar projects.

3. Government may also provide subsidy for such waste to energy technologies.

4. In order to ensure the performance of such plants, the Government may provide performance based incentives. This will ensure not only implementation but continuation of operation of these projects.

5. Government may consider FsDF a form of renewable energy source and benefits applicable to renewable energy projects may also be made available to FS waste to energy projects.

6. Government may regulate by providing limited licenses in a given region. This will ensure availability of FS for such waste to energy plants without affecting their availability.

7. The use of FsDF or blending of FsDF with other types of fuel like biomass, coal may be made mandatory in industries. This will create market for FsDF fuel. There may also be a provision for preferential tariff for power generated from FS based plant to increase their financial viability.

8. Participation of private players may be encouraged by implementing PPP model for development of such waste to energy projects with Government and Private players sharing risks and returns.

9. Such waste to energy projects may have many co-benefits in the form of avoided cost in O&M cost of STP, reduction in expenditure on health & hygiene, enhanced economic activity besides avoiding cost of installation of STPs. These co-benefits may be identified and quantified. The avoided costs by municipalities may be transferred to such waste to energy projects in terms of additional incentives.

   The government has mandated spending by companies registered under companies law at least 2 per cent of their net profit towards corporate social responsibility (CSR) activities under Companies Bill 2012[13]. Such waste to energy projects may be included under the definition of CSR activities. More companies would be encouraged to invest a part of CSR expenditure on such waste to energy projects.

[13] http://www.indianexpress.com/news/companies-bill-passed-with-mandate-on-csr-spending/1047290/1

4. Limitation

4.1. Limitations - HTC process

Collection and transportation

1. Only three sources for FS procurement have been selected in this Plug and Play model. Other procurement models can also be explored.

2. Solid content in sludge collected from septic tanks and MTVs are considered as 2% which is largely to vary. The plug and play model has been developed for 2% solid content. Hence any reduction in solid content needs to be reassessed.

3. The MTV usage has been assumed as 500 per day per MTV. However this is subject to various parameters which are beyond the control of MTV owner. Any reduction in MTV usage needs to be reassessed.

4. Revenue from septic tank collection:- At present, residents pay cleaning charges to tanker emptying agencies. However this may not cease off once they realize the commercial value of septic sludge.

5. O&M cost of MTV has been assumed as 3000 Rs/Month. This also includes the cost of care-taker (if any).

6. Revenue from per person usage in MTV:- As of now, the MTV model is not successfully working in India. This is due to poor maintenance of MTVs. Any further usage charges might result in low usage of MTV. This will have serious impact on revenue collection and this result in higher fuel production cost.

7. It has been assumed that FS will be procured from a radius of 10 km from plant site. In that case the plant location should be ideally in the center of urban area which is not possible. Hence the travelled distance need to assess based on actual distance from urban area.

8. It has been assumed that new trucks will be purchased for procurement of FS. However in local practice, people also purchase old trucks and modify it for carrying of septic sludge. However the cost of O&M is relatively. This aspect has not been considered in the Plug and Play model.

Pre-processing

9. Only one method for dewatering has been considered i.e. FCK-315-Rotary thickener. Local methods for dewatering should also be evaluated.

10. The capacity of FCK-315 dewatering process is 136 KLD whereas the required capacity is 45 KLD. Hence the selected capacity of dewatering system is oversized and the capacity should be selected appropriately. This will reduce the capital cost and O&M cost of dewatering system.

HTC

11. The hydrothermal carbonization technology has not been tested on FS at commercial scale and hence this needs to be tested and proven at pilot scale.

12. The HTC technology is appropriate for sludge with less than 80% of moisture. This may not work properly when the moisture content is high. Hence in case of non-functioning of dewatering system, the HTC system may not work properly.

13. In case of higher heating or longer holding time, the process may result in poor quality of fuel.

14. The HTC process will also generate liquid fertilizer. However the revenue from the same has not been considered in this Plug and Play model.

15. Land cost has been assumed however this is largely to vary depending on location of project site. Hence this should be evaluated for project specific site before implementation of project. However sensitivity analysis has been performed on total cost to cover such variations.

16. A large land area is required for natural drying, storage of fuel etc. An additional area of 500 m2 has been considered for such purpose. However this need to reconsider based on scale of project.

4.2. Limitations - Pyrolysis process

1. The bio-oil yield from FsDF has been assumed similar to bio-oil yield from chicken litter. However this assumption needs to be tested and proven.

2. The quality of bio-oil has been assumed similar to the industrial diesel. However the Bio-oil produced from the Pyrolysis may need further treatment.

3. Any deviation in control parameters like temperature, pressure, moisture may change the bio-oil yield and quantity of bio-oil yield.

4. Pyrolysis process has been successful for Pyrolysis of tyres. However there is no information on technology for Pyrolysis of FS. Hence It has been assumed that the costs (capital cost, fuel cost, O&M cost etc) related to Pyrolysis of FsDF are similar to the costs given for Pyrolysis of tyres. However this is not yet tested and verified.

5. The Pyrolysis process has not been tested on FS at commercial scale and hence this needs to be tested and proven at pilot scale.

6. Land cost has been assumed as 5400 USD. However this is likely to vary depending on the location and the price of land.

7. Char has been another source of revenue. However the market acceptability of this product is yet to be tested.

8. The raw feed to Pyrolysis plant has been considered as FsDF coming from HTC plant. Possibility of other technology options needs to be evaluated further to check viability in different pre-processing scenarios.