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Techno Economic Analysis of Cotton Stalk Biomass Based Bio-Oil Production Using Slow Pyrolysis Process

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ABSTRACT

In Indian context, green energy mission can be fulfilled through harvesting green energy from agriculture residue which is available abundantly. Slow pyrolysis may be a prominent technology to convert these low value agricultural biomasses into high value products such as Bio-oils, Pyro- gas and Bio-char, which finds vast applications as energy sources. Authors in this paper have presented a Techno-economic analysis of cotton stalk through slow pyrolysis process .Lab scale slow pyrolysis process was performed in batch scale Pyrolyzer at 500 °C temperature, 10 C°/min heating rate and 1-hour residence time as input parameters and Bio-Oil, Bio-Char and Pyro-Gas were obtained as output of slow pyrolysis process having process yields of 36.60 %, 37.78% and 25.25% respectively. Bio-oil and bio-char can be used to generate direct revenue, while pyro-gas may be used as energy source for process heating. Entire plant was assessed economically by considering n^{th} process plant assumption and 20 Tone/day capacities. Techno economic viability of plant was assessed by evaluating plant capital investment and operating cost. Plant capital investment was calculated based on total purchased equipment cost where as Total purchased equipment cost was calculated using equipment scale factor. Operating cost of entire plant was analyzed based on fixed capital investment. Plant economic evaluation was carried out by evaluating Minimum fuel selling price; Payback period and net present value. Estimated Minimum fuel selling price of the plant was ₹66.30/Liter ($ 0.068/liter), payback period of the plant was 3 years and Positive cash flow in Net Present Value.

Keywords: Techno Economic Analysis (TEA), slow pyrolysis, Cotton stalk, Payback period, Net Present Value (NPV)

INTRODUCTION

As per the report of energy information administration (EIA) bio-mass based energy consumption is expected to be increased by 4.4 % every year from 2009 to 2030 for end use market (Wright et al 2010). Currently, bio masses are mainly used for production of ethanol and bio diesel as green energy sources. In Brazil and USA, Bio-ethanol is produced from 1st generation (1G) food crop i.e. sugarcane, corn, wheat etc. which is used as transportation fuel due to its potential to mitigate environmental issues. However, increased application of 1G crop for bio ethanol production has raised food vs. feed issues, specifically in developed countries (Bezerra et al 2016). In order to address the issue, lignocelluloses biomass, considered as 2nd generation (2G) biomass, may be used for production of Bio-ethanol or Biodiesel. The major feedstock for 2G category biomass is agricultural residues like straw, stalk, leaves, forest residue (chips, logging residue etc.) and energy crop like switch grass, rapeseed etc. As per energy mandate act 2007 at least 36 billion gallons' renewable fuel to be produced from cellulosic and lignocelluloses based biomass by 2022(Krishna et al. 2016). Slow pyrolysis is a process used for conversion of lignocelluloses based biomass into naphtha and diesel fuel.

India, being agricultural based economy, Agro waste residues is available abundantly throughout the year as an inexpensive source for green energy harvesting. However, some of the biomass in 2G category of agriculture residues is used as animal fodder. Hence in India, with huge population of domestic animals, it creates food vs. feed issue. However, many of biomasses in 2G category, i.e. Non-edible agro residues like cotton stalk residue, wheat straw, rice straw etc., cannot be used as animal fodder either due to its toxic elements or low nutritional values. India is the largest cotton producing country in the world; hence abundance quantity of cotton stalks is available as bio mass. As per estimation, every hectare of cotton production generates 2MT of cotton stalk (Binod et al. 2012). Currently, post-harvest cotton stalks residues are burnt on the fields which degrade soil nutrient values and create detrimental effects on air and land pollution. To offer solution to these issues, many researchers have tried pyrolysis process to convert cotton stalk residues in to useful green energy products and thereby production of green fuel. El-Kalyoubi et al. 1985, Ren et al. 2009, Lu, Q et al 2009. Chen, Y et al 2012, Putin et al. 2005, et al. Zheng et al. 2008, Wang et al. 2006, Shuangning et al. 2006, Fu, P. et al. 2012, Balagurumurthy et al. 2014 found that utilization of cotton residue in slow pyrolysis would reduce longer transportation of locally available cotton residue. But economic feasibility of slow pyrolysis process should be thoroughly investigated.

Techno Economic Analysis (TEA) is a tool used to assess technical and economic performance of any process pathway. This study is focused on the production of diesel range biofuel from slow pyrolysis of cotton stalk. Several studies are available for economic analysis of bio-oil production via fast pyrolysis from surplus residue (Islam et al. 2000, Negahdar et al. 2016, Zhang et al. 2013). Previously reported study of fast pyrolysis process has estimated production cost of bio-oil between \$0.64/L - \$1.03/L (₹46.08/L – 74.16/L) for the capacity of 2000 t/day with total project investment between \$106 million-\$500 million (Wright et al. 2010; Thilakaratne et al. 2014; Brown et al. 2013; Swanson et al. 2010). However, less work has been reported for slow pyrolysis process for production of bio oils from agro waste biomasses. In recent years, slow pyrolysis process has gained lots of interest by researchers because of higher yield of bio-char along with bio-oil and pyro-gas as by-product. Bio-char can be used as soil amendment element for increasing soil fertility and reduces chemical fertilizer requirement (Spokas et al. 2012). In current article TEA was carried out by calculating Plant Capital Investment and Operating cost and it was compared with fast pyrolysis plant. The main objective of this article is to evaluate techno economic viability of cotton stalk slow pyrolysis process as transportation fuel by calculating Net present Value (NPV), payback period and minimum fuel selling price etc.

MATERIAL AND METHOD

PYROLYSIS PROCESS

Assumed biomass conversion plant capacity is 20t/day using cotton stalk as feedstock. Major steps involved in the process are biomass pre-processing, pyrolysis process, solid removal, oil collection, Bio-oil up gradation, and pyro-gas recirculation. Figure 1 shows Industrial scale pathway for slow pyrolysis process, while Figure 2 shows lab scale pyrolysis process plant. Reactor is the heart of the slow pyrolysis process; however, pretreatment is also very important process steps that involve biomass washing, drying, milling and screening. Feedstock washing is done to washout impurities present in it. After washing, it is to be dried by industrial scale drier. For efficient pyrolysis process recommended moisture content should be less than 7%. (Swanson et al 2012). Dried Biomass is required to be converted into particle size less than 3 mm to maximize yield and for uniform heat distribution during pyrolysis process. Hence, pretreatment is an essential step before biomass enters into process line. Slow Pyrolysis process is performed at 500 °C temperature with heating rate 10 °C/min, and residence time 1 hour. Pyrolysis process yield was calculated as per equation 1, 2 & 3. Standard cyclone was used to remove solid particles trapped in vapors. Vapors are condensed in two condensers and finally bio-oil collected and stored at ambient temperature in vessels prior to the up gradation.

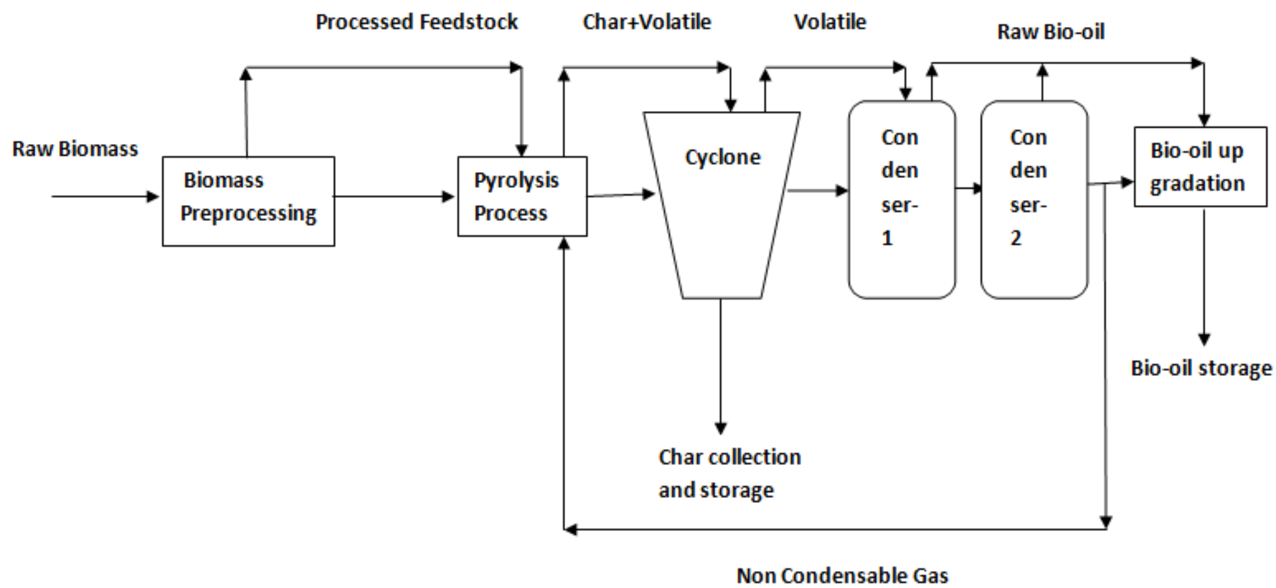

FIGURE 1. Line diagram of industrial scale pyrolysis process plant

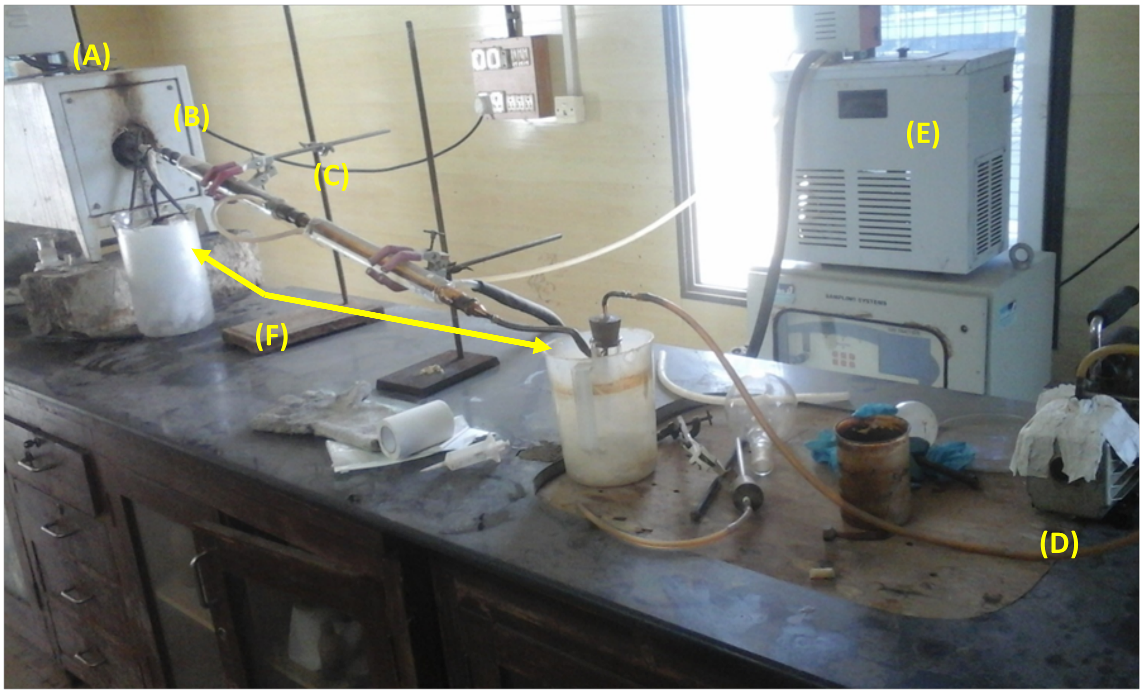

FIGURE 2. Lab scale pyrolysis process reactor

Fixed Bed Reactor, (B) Reactor Outlet, (C)Glass condenser, (D) Vacuum Pump, (E) Chiller, (F) Bio-oil collecting vessel

$$\text{Bio-char Yield, wt\%} = \frac{m_{bio-char}}{m_{feedstock}} * 100 \qquad \text{Equation (1)}$$

$$\text{Bio-oil Yield, wt\%} = \frac{(Weight\ of\ cylinder\ with\ with\ bio-oil)-(Weight\ of\ empty\ cylinder)}{(Weight\ of\ feedstock)} * 100 \qquad \text{Equation (2)}$$

$$\text{NCG yield, wt\% =100 - (bio-oil yield, wt \% + bio-char yield, (\%)} \qquad \text{Equation (3)}$$

Pyrolysis process produces bio-char and pyro-gas along with bio-oil. Produced bio-char was collected and stored in vessels and pyro-gas was re-circulated for biomass heating source during pyrolysis process and bio-char may be sold as per market price for further usage. Table 1 enlists equipment and machinery required before and after pyrolysis process. Bio-oil composition shows significant presence of moisture and oxygenated compound that are undesirable for combustion in vehicle engine. Hence bio-oil needs to be upgraded before it is used as fuel. Out of many up-gradation processes, emulsification is the most promising and reliable route that produce bio-oil diesel emulsion at limited cost. Composition of Produced pyro-gas shows presence of methane (CH_4) and carbon dioxide (CO_2) that reveals its suitability for biomass heating during pyrolysis process. Presence of Carbon as main element in bio-char elemental analysis indicates that it may be suitable as soil nutrient and fertilizer.

TECHNO ECONOMIC ANALYSIS (TEA)

To check feasibility of any process techno-economic analysis is an essential tool that evaluates cost associated with the entire plant and compares configuration of process. The major benefit of TEA is that it provides risk associated with process without constructing physical plants. Also it provides scope to improve the process model (López-Ordovás et al. 2019). A profitability of any plant can be determined by evaluating cost. Figure 3 shows classification of the cost.

TABLE 1. List of equipment required

Process Stage	Equipment	Unit
Pretreatment Unit	Crushing	Mill
(Include crushing, Sieving)	Screening	Sieve
Reaction	Reactor	Pyrolyzer
Storage	Storage Tank	Feed Tank
		Char Tank
		Oil Tank
Separation	Centrifuge	Cyclone
	Heat Exchanger 1	Condenser 1
	Heat Exchanger 2	Condenser 2
Moisture Free bio-oil recovery	Rota evaporator	Recovery of bio-oil

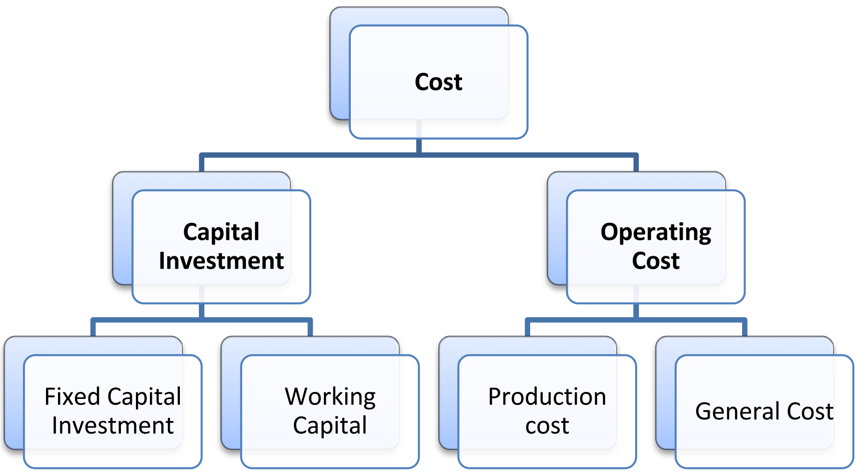

FIGURE 3. Classification of cost elements

CAPITAL COST

Capital cost covers the cost associated with equipment purchase, its installation and the cost to start up the plants. It can be further classified into two costs. Fixed Capital Investment (FCI) and working capital cost. All the cost connected with design, Installation, Construction including all engineering cost and contingency cost fall under FCI. While working capital is the other contributor of capital cost that involves cost after the accomplishment of construction i.e. material cost, salaries and wages, the money for emergency etc. FCI further classify as direct cost and indirect cost. Direct cost associated with installation of plant and indirect cost associated with construction, insurance etc. Purchased equipment cost calculated using scaling factor equation 4. While the other direct and indirect cost calculated using cost factors of FCI and Total purchased equipment cost shown in Table 2.

$$\text{Present Cost} = \frac{\textit{Original Cost} * \textit{Present index value}}{\textit{Index value at the time of equ.purchase}} \qquad (4)$$

OPERATING COST

Operating cost is the cost associated when the plant is in operation. It can be divided into production cost and general cost. Production cost is directly related to production process while general cost considers research, administration and sales etc. Table 3 shows parameters considered for calculating operating cost.

MINIMUM FUEL SELLING PRICE (MFSP)

MFSP is the lowest price of fuel at zero Net Present Value (NPV) and predetermined Internal Rate of Return (IRR). MFSP is a function of plant capital cost and operating cost. It is used to determine economic feasibility of biofuel pathway by comparing it with petroleum based product. MFSP is less suitable for quantifying biofuel pathway over period of several years as pathway products are highly volatile with market rather than being static (Brown et al 2013).

TABLE 2. Cost factors for capital investment (Bejan et al. 1995; Peters et al. 2003)

	Components	Cost factors	Assumed cost factors (%)
1.	Fixed Capital Investment (FCI)		
1.1	Direct Fixed Capital Investment (DFCI)		
	• Purchased Equipment cost (PEC)	15-40 % of FCI	Calculated using eq.(1)
	• Purchased equipment Installation	20-90 % of PEC	45% of PEC
	• Instrumentation and control (Installation)	6-40% of PEC	10% of PEC
	• Piping	10-70 % of PEC	31 % of PEC
	• Electrical	10-15 % of PEC	10% of PEC
	• Yard improvement	2-5 % of FCI	0
	• Service facilities	30-100 % of PEC	20% of PEC
	• Land	0-2% of PEC	0
1.2	Indirect Fixed Capital Investment (IFCI)		
	• Engineering and supervision	25 -75 % of PEC	30% of PEC
	• Construction expense& Contractor's fee	15% of DFCI	15% of DFCI
	• Contingency	8-25% of Direct and indirect cost	10% of Direct and indirect cost
	Total Fixed Capital Investment (FCI) = DFCI+IFCI		
2.	Working Capital		
	• Startup cost	5-12 % of FCI	10% of FCI
	Total Capital Investment = FCI+Working Capital cost		

PAYBACK TIME

It calculates time required to recover initial investment. It is the simplest method to determine the profitability of the project. However, it does not include the factors like interest rate, plant life etc. Desirability of investment is decided by payback period. Shorter payback period means more attractive investment. It is the length of a time at which investment reaches at breakeven point.

TABLE 3. Cost factors for operating cost (Islam et al 2000)

Sr. No.	Parameters	Factors
1	Plant Capacity	20t/day
2	Annual operating time	312 days/year
3	Maintenance labor	1% of FCI
4	Maintenance materials	3% of FCI
5	Overheads	2% of FCI
6	Insurance	2% of FCI
7	Other fixed operating costs	1% of FCI
8	Interest rate	10%
9	Feedstock cost	20 US$/ton
10	Labor hire rate	1 US$/h
11	Electricity price	0.04 US$/kWh
12	Plant Life	30 years
13	Chemical Engineering Plant Cost Index (CEPCI)	607.5

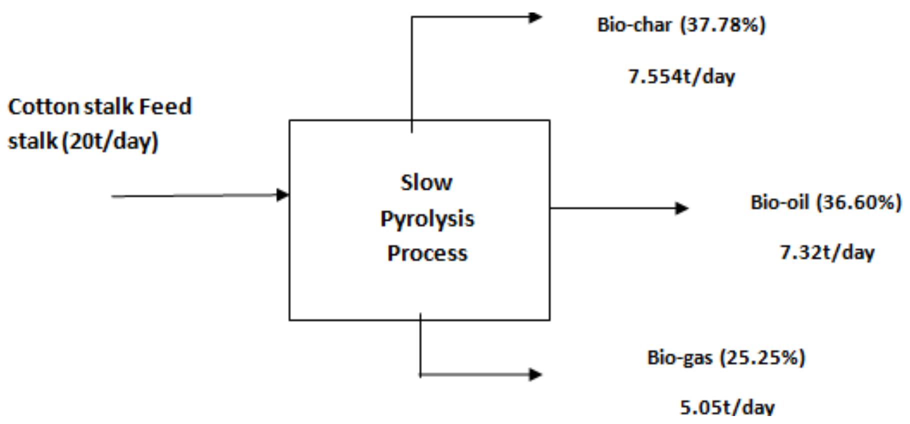

FIGURE 4. Pyrolysis process yield

NET PRESENT VALUE (NPV)

NPV is defined as a worth of project at the end of project life. Cash flow of the project and discounted rate of interest are considered while calculating NPV. This is the representation of time value for money. It can be calculated using eq.5. It is desirable that value of NPV is positive.

$$\text{Net Present Value (NPV)} = \sum_0^n \frac{(NetCashFlow)_n}{(1+r)^n} \quad (5)$$

RESULT AND DISCUSSION

PYROLYSIS PROCESS

Cotton stalk slow pyrolysis process yield is shown in Figure 4. Process was performed at 500 ° C temp. Bio-oil derived via pyrolysis process was up-graded and stored in vessels. Produced bio-char collected and stored in vessels while bio-gas was re-circulated. Stored bio-oil and bio-char were sold to produce revenue

ECONOMIC ASSESSMENT

CAPITAL COST

Total capital cost of slow pyrolysis process plant can be calculated in correlation with total purchase Equipment cost (TPEC). TPEC calculated using equation 4. List of equipment and its cost to operate slow pyrolysis plant having 20t/day capacity enlist in Table 4. Total calculated TPEC cost is ₹332.46lakhs Fixed direct and indirect capital investment was calculated with reference to TPEC as mention in table 2. Total calculated capital investment is ₹656.86 lakhs. Detail calculation of total capital investment shown in Table 5.

OPERATING COST

Operating cost to operate 20t/day pyrolysis plant listed in Table 6. Operating cost for the plant calculated considering n^{th} plant assumption as mentioned in the table 3. Total operating cost is ₹162.2lakhs. Pyrolysis process produced bio-oil, bio-char and pyro-gas. Entire electricity requirement of pyrolysis process will be fulfilled by pro gas while bio-char to be sold in market to generate revenue. Bio-char selling price were finalized using bio-char offset value projected by American Clean Energy and Security Act (ACESA). As per ACESA cost of bio-char for 2021 would be $ 34 /Metric ton (Brown et al 2011). Hence, final operating cost of the plant after considering revenue bio-char is ₹112.4 lakhs.

TABLE 4. Total purchased equipment cost (TPEC)

Process	Components	Estimated price (Lakhs ₹)	Reference
Preprocessing	Mill + Screen	18.49	[28]
Pyrolysis	Reactor	53.30	[28]
Storage	Feed storage	58.74	[28]
	Bio-oil Storage	44.67	
	Bio-char storage	52.14	[28]
Separation	Cyclone	52.79	
	Condenser 1	24.44	
	Condenser2	23.57	
Bio-oil recovery	Seperator+Rota evaporator	4.32	Vender
	TPEC=	332.46	

TABLE 5. Total capital investment/project Cost

	Parameters	Cost (Lakhs ₹)
Direct Fixed Capital Investment (DFCI)	Purchased equipment Installation	149.6
	Instrumentation and control (Installation)	33.2
	Piping	103.06
	Electrical	33.2
	Service facilities	66.4
	Total DFCI	385.46
Indirect Fixed Capital Investment (IFCI)	Engineering and supervision	99.6
	Construction expense & Contractor's fee	57.81
	Contingency	54.28
	Total IFCI	211.69
	Total Fixed Capital Investment (FCI)	597.15
Working Capital Investment	Startup cost	59.71
	Total Working Capital Investment	59.71
	Total Capital Investment	656.86

MINIMUM FUEL SELLING PRICE (MFSP)

Minimum fuel selling price is calculated based on total operating cost. MFSP of plant was estimated and it was compared with rise husk fast pyrolysis plant having capacity 24 t/day and wet wood plant having capacity 100 t/day. MFSP of current plant having 20 t/day capacity is ₹66.30/ liter ($0.26/ gallons). Comparison shows capital cost of slow pyrolysis process is too much less compare to fast pyrolysis plant while there is no major change in operating cost between rice husk plant and cotton Stalk plant while it shows considerable difference in wet wood plant. Even though reduction in bio-oil production cost for slow pyrolysis due to revenue generated by selling of bio-char. Figure 5 shows comparison between slow pyrolysis of cotton stalk plant and fast pyrolysis of rice husk plant and wet wood plant.

PAYBACK-TIME

Payback period was calculated based on cumulative cash flow considering gross profit and capital investment. Gross profit was calculated by considering revenue generated by selling bio-oil. Assumed selling price for bio-oil was 1 ($/gallons) and it increased every year by 0.3 factor. As describe in Figure6 cumulative cash flow of proposed plant increased year by year while capital investment will remain constant. It can be reveal from Figure that payback time for project is approx. 3 years. Hence investor will starts receiving profit from 3rd year onwards. Ibrahim Dincer et al suggested payback score 0.76-1 if payback time is less than 6 years.

TABLE 6. Operating cost

Cost factors	Cost (Lakhs ₹)
Maintenance labor	59.71
Maintenance materials	179.14
Overheads	119.42
Insurance	119.42
Other fixed operating costs	59.71
Feedstock Cost	89.85
Electricity requirement	Fulfill by pyro-gas.
Total Operating cost	162.2
Bio-char yields	36.60%
Price of Bio-char ($/Metric Ton) for year 2021	34
Revenue generated by bio-char	49.8
Final Operating cost after selling of bio-char	112.4

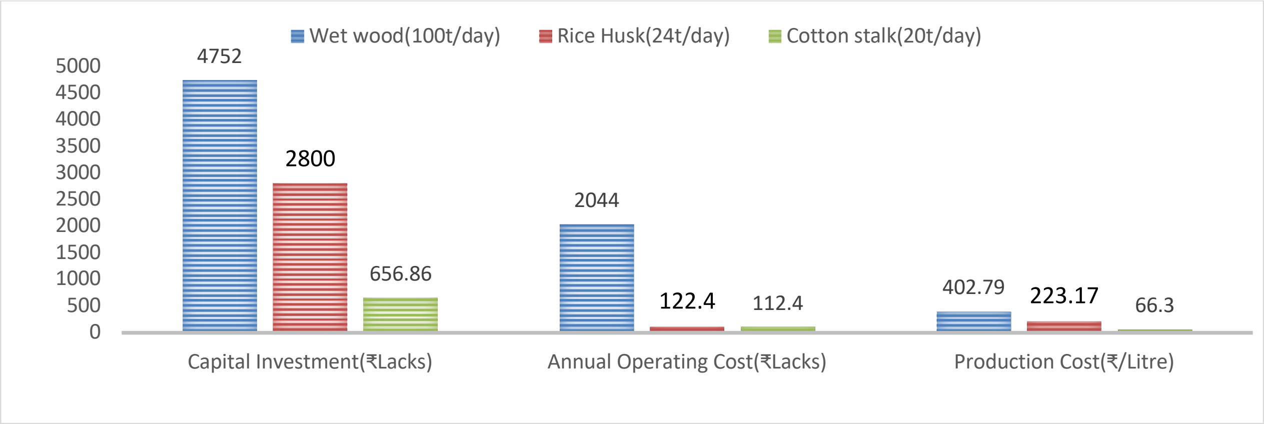

FIGURE 5. Comparison of rice husk and cotton stalk pyrolysis plant

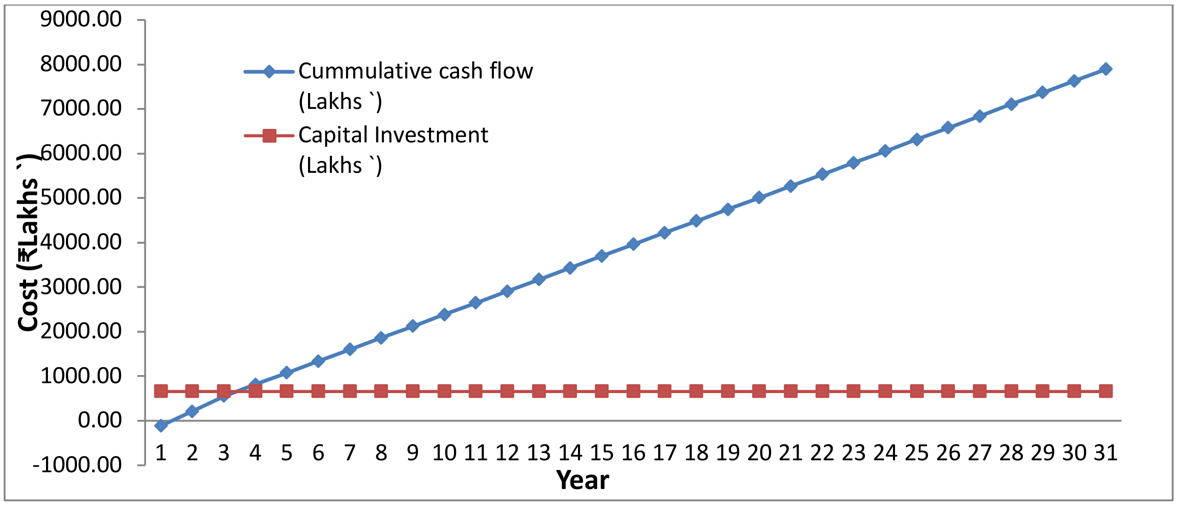

FIGURE 6. Payback period of pyrolysis process plant

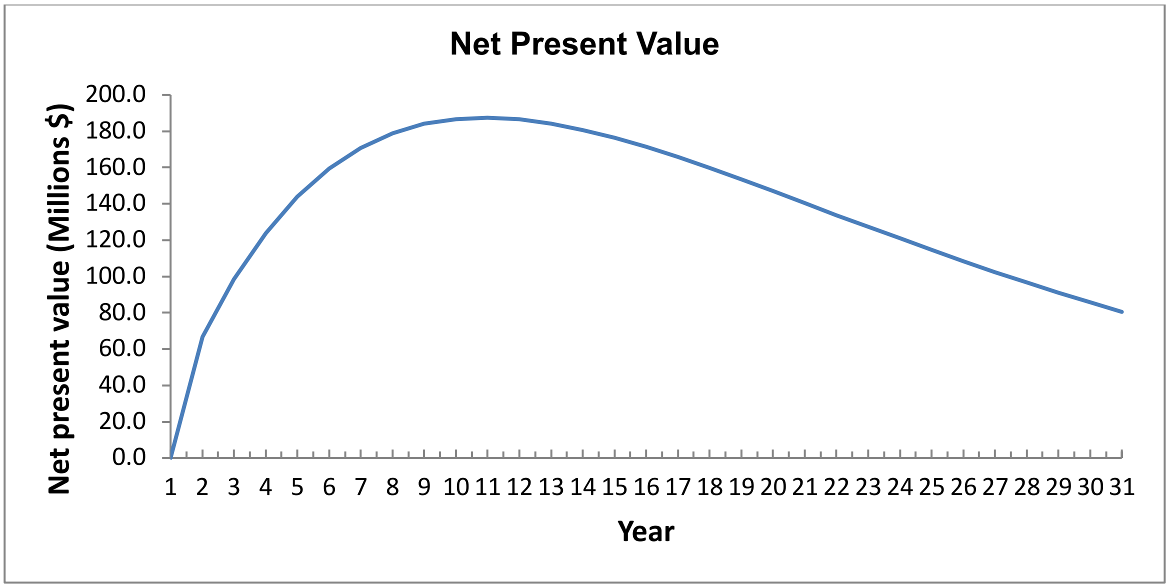

FIGURE 7. Net present value of the pyrolysis plant

NET PRESENT VALUE (NPV)

Cash flow diagram prepared after consideration of total operating Cost and 35% taxation. And present value of project calculated considering project life as 30 years, discounted rate of return considered as 10%. Gross profit calculated by considering revenue generated from bio-oil. It clears from Figure7 that project inflow value is positive for each year till 10 year then it starts to decline. May be due to depreciation of equipment. Positive cash inflow in NPV shows probability of good rate of return and economic viability of project.

CONCLUSIONS

The following points were concluded from TEA of slow pyrolysis process of 20ton/day capacity plant:

1. Cotton stalk can be used for the production of green fuel via slow pyrolysis process at 500°C, 10 °C /min heating rate and 1-hour residence time.
2. Slow Pyrolysis process of Cotton stalks produce bio-oil, bio-char and gas with process yields of 36.60 %, 37.78% and 25.25% respectively.
3. Techno-economic analysis of slow pyrolysis process was performed considering n^{th} plant assumption and 20t/day plant capacity. Capital cost and operating cost of the plant were estimated with reference to total purchased equipment cost, which was calculated using Chemical engineering plant cost Index (CEPCI) 607.5.
4. Estimated purchased equipment cost was ₹332.46lakhs. While Total cost of capital investment and plant operating were ₹656.86 lakhs, and ₹162.2 lakhs respectively.
5. ACESA has estimated selling price for bio-char and bio-oil for the year 2021 that was$ 34/metric ton. Hence, Final operating cost of entire plant after considering revenue from bio-char is ₹112.4 lakhs.
6. Based on operating cost, minimum fuel selling price was calculated (MFSP). And found to be ₹66.30 /liter.
7. Feasibility of the plant was investigated by evaluating payback period and Net Present Value (NPV) of the plant. Estimated payback period of the plant was 3 years, which motivates the investors for investment in the field of Bio oil production. While positive graphs of Net Present value of plant during entire plant life shows significant rate of return.
8. At last it can be concluded that capital investment, operating cost and MFSP of proposed plant are less as compare to previously reported article. Whereas 3 years payback period and positive NPV for proposed plant shows strong viability of plant.

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DECLARATION OF COMPETING INTEREST

None

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