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Performance Evaluation and Techno-Economic Feasibility of a Developed Fast Pyrolysis Unit for Lemongrass Pyrolysis

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Abstract - *Pyrolysis is thermal decomposition of biomass conducted in absence of oxygen at temperature of 400-600 °C for very short residence time of 2 seconds to produce bio-oil. In this study, pyrolysis of lemongrass was investigated with the aim to study the product distribution and their chemical compositions and to identify optimum process conditions for maximizing the bio-yield. Particular investigated process variables were temperature (450°C), heating rate (10-50°C/min) and nitrogen gas flow rate (2.5 l/min). Proximate analysis and heating value of both bio-oil and raw material was investigated. The fuel properties of bio-oil such as flash point, fire point, viscosity, cloud point, pour point etc was also determined. The performance evaluation was carried out a proximate analysis of lemongrass and characterization of lemongrass oil and it was found that bio-oil (26.53%), bio-char (34.61%) produced from lemongrass. The properties of lemongrass bio-oil were viscosity (29.9 cSt), flash point (294°C), fire point (353°C), cloud point (-7.2°C), pour point (-15.0°C), and Calorific value (26.5MJ/kg). It has been found that raw lemongrass contains Moisture content, volatile matter, ash and fixed carbon content 9.97, 83.88, 4.43and 11.69 % respectively. The lemongrass and such herbal and medicinal plants were presented as an environmentally friendly feedstock candidate for bio-oil.*

Keywords: **lemon grass; pyrolysis; bio-oil, characterization, fixed-bed, economics analysis, etc.**

INTRODUCTION

Biomass is viewed as a major world renewable carbon-neutral energy source. Combustion of fuels derived from biomass is believed to be less polluting than that of fossil fuels. For these reasons conversion of biomass into fuels is gaining significant popularity worldwide. Biomass has always been an important energy sources for India considering the benefits it offers for power generation, cooking gas production and other valuable recycled products. It is renewable, widely available, carbon neutral and has potential to provide significant employment in the rural areas.

Pyrolysis is thermal decomposition conducted in absence of oxygen at temperature 400-600°C for very short residence time of 2 seconds to produce liquid major product bio-oil. Pyrolysis of biomass leads to formation of bio-char and vapors consisting of condensable and non-condensable gases. Quenching of vapors after its separation from char yields a liquid product which is known as bio-oil. Also a gaseous by-product that is referred to as non-condensable gas is obtained after quenching.

In the present context the utilization of bio-oil especially for power production or thermal application is still under development and need further study for the standardization and quality improvement. However, bio-oil can substitute fuel oil or diesel in many static applications including boilers, furnaces, engines and turbines for electricity generation. Bio-oil is an attractive alternative energy source for many reasons. Most notably, it is completely renewable and easily created from common waste products. Using biomass feed stocks such as wood, wheat straws, and ground-nut shells. The pyrolysis process results in "net zero" carbon dioxide emissions. Keeping above points in mind research problem is formulated to design and develop fixed bed type fast pyrolysis unit for production of bio-oil by using crop residues.

MATERIALS AND METHODS

A] Design of fixed-bed fast pyrolysis unit

i. Design of reactor Choice of reactor type

Choice of a reactor depends on several factors such as type, capacity, capital cost, yield and available feedstock, bulk density, volume. For example, a choice made from capital cost consideration may not give the best operating cost or highest yield, while one with the highest yield may not suit the available feedstock or may require high capital investment. Applying proper weight age to a selection criterion, one could make a final selection.

Heat transfer in reactor Conduction, Q Cond

$$Q_{cond} = -kA\frac{\Delta T}{x}$$

The height of reactor

$$h = \frac{V}{\pi r^2}$$

Total volume of reactor

$$V_R = \pi r^2 h$$

Capacity of reactor

$$\text{Bulk density} = \frac{\text{Mass}}{\text{Volume}}$$

Thickness of insulation, rc

$$r_c = \frac{\text{Thermal conductivity of cerawool}}{\text{Heat transfer coefficient}}$$

Outer diameter of reactor

$$D_O = r_c + D_{reactor} + r_{critical}$$

ii. Design of Heat Exchanger

Length of tube of was calculated by using following method (Cengel, 2007).

Heat capacity rate of hot fluid

$$C_h = m_h Cp_h$$

Heat capacity rate of cold fluid

$$C_c = m_c Cp_c$$

Capacity ratio

$$c = \frac{C_{min}}{C_{max}}$$

Maximum heat transfer rate

$$Q_{max} = C_{min}(T_{hin} - T_{cin})$$

Actual heat transfer rate

$$Q = [mc_p(T_{out} - T_{in})]_{water}$$

The effectiveness of heat exchanger

$$\epsilon = \frac{Q}{Q_{max}}$$

Number of Transfer Units (NTU)

$$NTU = \frac{UA_S}{C_{min}}$$

Heat transfer surface area, As (m2)

$$A_S = \frac{NTU \times C_{min}}{U}$$

Surface area, As

$$As = \pi DL$$

Length of the tube (m)

$$L = \frac{A_S}{(\pi \times D)}$$

B] Performance evaluation of developed pyrolysis unit

Proximate analysis biomass

1. Moisture content (%)
2. Volatiles
3. Fixed carbon
4. Ash

Properties of bio-oil

1. Viscosity
2. Flash point
3. Fire point
4. Cloud point
5. Pour point
5. HHV of liquid (MJ/kg)

C] Cost Economics of designed system

The following assumptions were made for economic assessment of designed system.

a. Discount rate (d)
b. Repair and maintenance (α) 5% of the capital cost of Pyrolysis system
c. Number of days of operation per year, (n)
d. Life span (t)
e. Capital cost of the biomass fired dryer (C0)

1. The Net present value

$$NPV = \left(\frac{np - C_0\alpha}{d}\right)\left[\frac{(1+d)^t - 1}{(1+d)^t}\right]$$

2. The Benefit- Cost ratio

$$\text{Benefit cost ratio} = \frac{\Sigma\,(B - C')}{C_o}$$

3. The payback period (PP)

$$PP = \frac{C_0}{(np - \alpha C_0)}$$

RESULTS AND DISCUSSION

A] Design of Fast pyrolysis unit

The Fixed-bed type Fast Pyrolysis unit to produce clean and high energy Bio-oil from crop residue was designed by the Department of Renewable Energy Engineering, CTAE, and MPUAT Udaipur. The designed unit was fabricated by M/s Siya Instrument, Udaipur. The unit comprises of fixed bed type reactor, Heat exchanger for condensation, K-type thermocouples for measuring reactor temperature, water pump, and bio-oil receiver for collecting oil.

The reactor system is operated through controlled systems. The pressure of N2 sweeping gas is controlled by the pressure gauge as per required. A temperature indicator cum controller is connected to K-type of thermocouple to control the temperature of reactor. The complete system is shown in fig.1. The lemongrasses (5kg) are used as raw material. The feed rate is adjusted to 5kg/hr. The temperature was set at 450°C. The bio-oil is collected at the bottom of the condenser. The performance of heat exchanger was evaluated by coupling it with bio-char reactor. Chilled water at 8°C is re-circulated in the outer water jacket of heat exchanger for condensation of pyrolysis vapor and recovery of bio-oil has been observed as 26.72% for groundnut shells, 24 % for sorghum and 26.53% for Lemongrass. Technical Specifications of developed Fast pyrolysis system are mentioned in table. 1

Fig. 1 Developed Fixed-bed Type Fast Pyrolysis Unit

Table 1 Design Parameters of the Developed Pyrolysis System

Design Parameter	Value
Reactor	
Capacity of reactor (kg/h)	5
Capacity of heating coils (kW)	10
Pyrolysis temperature (°C)	450–600
Particle residence time (s)	50–300
Vapour residence time (s)	< 2
Heating rate (°C/s)	500
N_2 gas flow rate (L/min)	2.5
Bulk density of material (kg/m^3)	86
Inner cylinder diameter (m)	0.35
Outer cylinder diameter (m)	0.46
Perforated pipe diameter (m)	0.05
Insulation thickness over heating coils (m)	0.05
Height of reactor (m)	0.55
Heat Exchanger	
Inner pipe diameter (m)	0.025
Outer pipe diameter (m)	0.075
Pipe length (m)	1

[B] Performance evaluation of Fast pyrolysis unit

The produced yield of bio-oil, bio-char and syngas from lemon grass is given in table2.

Table 2 Performance analysis of developed Pyrolysis unit

Biomass used	Output		
	Groundnut shells	Sorghum straw	Lemongrass
Average temperature (°C)	450	450	450
Residence time (sec)	2	2	2
Initial mass fed in reactor (kg)	4.34	3.70	5.34
Bio-oil found (kg)	1.16	0.90	3.23
Bio-char found (kg)	1.64	1.13	1.12
Bio-oil recovery (%)	26.72	24.32	26.53
Bio-char yield (%)	37.78	30.54	34.61
Gas yield (%)	37.78	45.13	38.84
HHV of Bio-oil (MJ/kg)	26	32	24.5

The experiment was carried out at temperature of 450°C with heating rate 50°C/min and nitrogen taking as sweeping gas with flow rate of 2.5L/min for 60 min. Bio-oil yield from lemongrass was found about 26.53% and bio-char was about 34.61% and syngas 38.84% it is shown in figure 2.

Figure 2 Bio-oil and bio-char from lemongrass

The physio chemical properties of biomass and thermal properties of bio-oil like moisture content, calorific value, viscosity, cloud point, pour point, fire point, and flash point has been observed and given in this study.

a] Proximate analysis of biomass

Properties of biomass as per different studies conducted by using various instruments like hot air oven, moisture analyzer, muffle furnace, weighing balance are given in the Table3.

Table 3 Properties of biomass

Sr. No	Biomass	Moisture content %	Volatile matter %	Ash %	Fixed carbon %
1.	Groundnut shells	10.41	86.07	3.52	10.41
2.	Sorghum straw	10.89	83.6	5.5	10.9
3.	Lemongrass	9.97	83.88	4.43	11.69

b] Properties of bio-oil

As per different studies conducted at the laboratory the properties of different biomass and bio-oil are given in the Table 4.

Table 4 Properties of Bio-oil

Sr. No	Parameter	Groundnut shells	Sorghum straw	Lemongrass
1	Viscosity, cSt at 40°C	31.2	32.3	29.9
2	Cloud point °C	-1.1	-3.9	-7.2
3	Pour point °C	-40.0	-12.2	-15.0
4	Fire point, °C	321	223	353
5	Flash point °C	277	254	294
6	HHV of bio-oil MJ/Kg	39.5	26	26.5
7	Moisture content %	7.5	8.2	9.2

C] Economic feasibility of system

The economics evaluation of developed pyrolysis unit was carried out in terms of net present worth, payback period, cost benefit ratio and internal rate of return, as procedure suggested by Panwar et al. (2014).

Table 5 Economics of Fast pyrolysis unit

Sr. No.	Economics parameter	Output
1.	Capital cost of Pyrolysis Unit	Rs. 2,86,000
2.	Number of days of operation in a year	300 days
3.	Life of developed Pyrolysis Unit	5 years
5.	Repair and Maintenance Cost(@10 % of capital cost per year)	Rs. 28,600
6.	Cost of Lemongrass including its transportation and labour cost	Rs. 5 Per kg
7.	Total operation per year	1500
8.	Total lemongrass required on annual basis	7500 kg
9.	Cost of Lemongrass per year	Rs. 37,500
10.	Cost of Nitrogen Cylinder (@ Rs. 2000 per cylinder)(One cylinder per day)	Rs. 6,00,000
11.	Electricity consumption per batch	10 unit
12.	Total electricity cost per year	Rs. 1,20,000
13.	Labour Cost required per day to operate Unit (@ Rs. 300 per day)	Rs. 90,000
14.	Total operation cost per year	Rs. 8,76,100
15.	Bio-oil produced per day (@ 6.0 kg)	1800 kg
16.	Market value of Lemongrass oil per kg.	Rs. 2000
17.	Total cost of Lemongrass oil per year	Rs. 36,00,000
18.	Pay Back Period	330.65 days ≈ 1.10 years
19.	Benefit Cost Ratio	3.78

Table 6 Economic indicators of the developed pyrolysis unit

Sr. No.	Economic Indicators	Value
1	Net present worth (NPW)	Rs. 10039724.08
2	Benefit cost ratio (BCR)	3.78

3	Pay-back period (PP)	1.10 Years
4	Internal rate of return (IRR)	856.73%

The net present worth and internal rate of return of the developed system was found Rs. 10039724/- and 856.73 per cent respectively for 5 years assumed life of developed system. The benefit-cost ratio was found to be 3.78 with a payback period of 1.10 years (330 days) which are viable and feasible as well.

CONCLUSIONS

In this study pyrolysis of lemongrass were carried out in a fixed-bed reactor in order to investigate the effect of pyrolysis temperature, heating rate, and sweeping gas flow rate on product yield and to study proximate analysis of lemongrass and characterization of bio-oil produced from lemongrass.

The experiment was carried out at temperature of **450°C** with heating rate **50°C/min** and nitrogen taking as sweeping gas with flow rate of **2.5L/min for 60 min**. **Bio-oil yield from lemongrass was found about 26.53% and bio-char was about 34.61%.** The viscosity, flash point, fire point, cloud point, pour point, and calorific value was estimated about **29.9 cSt, 294°C, 353°C, -7.2°C, -15.0°C, and 26.5 MJ/kg** respectively. It has been found that raw lemon grass contains Moisture content, volatile matter, ash and fixed carbon content **9.97, 83.88, 4.43and 11.69 %** respectively. **The NPW for the system was found Rs. 10039724/- for 5 years assumed life of developed system.**

Pyrolysis encourages the production of Bio-oil with medicinal and herbal plants like basil, mint lemongrass etc. used in medical purpose to benefit farmers for their self-economic development. Pyrolysis encourages the production of Bio-oil with medicinal and herbal plants like basil, mint lemongrass etc. used in medical purpose to benefit farmers for their self-economic development.

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BIOGRAPHIES

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