

## THE FUEL PROPERTIES OF PYROLYTIC OILS DERIVED FROM CARBONACEOUS SOLID WASTES IN BANGLADESH

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**Abstract.** The carbonaceous solid wastes in the form of rice-straw, jute-stick and bagasse were pyrolyzed in a fluidized bed reactor. The condensed oils were analysed for their properties as fuels and compared with other biomass derived pyrolytic oils and refined petroleum products. The fuel properties compared were physical properties, calorific value, elemental (CHNOS) analysis and chemical composition using Fourier Transform InfraRed (FTIR) spectroscopy. The results showed that the pyrolysis of biomass may be a potential source of liquid hydrocarbon fuel.

*Keywords:* Biomass, pyrolytic oils, fuel properties, CHNOS, FTIR

### 1.0 INTRODUCTION

Fast pyrolysis of biomass solid wastes is considered as an emerging potential technology for liquid oil production. Bangladesh is an agriculture-based country. The major agricultural residues or by-products of this country are rice-straw, jute-stick and bagasse. The conventional uses of these biomass solid wastes are as fuel for cooking, cattle feed, raw material for paper and pulp industries and a huge amount is unused and wasted that creates disposal problem [1]. In 1998 – 99, the production of these by-products in Bangladesh were 25 876.50, 1218.00 and 1390.20 thousand metric tons respectively, [2]. These carbonaceous solid wastes are renewable energy source and therefore, the potential of converting them into useful energy such as liquid fuel should be seriously considered. In this way, the wastes would be more readily usable and environmentally more acceptable.

The proximate analysis, elemental composition and thermogravimetric analysis (TGA) of the biomass solid wastes show that these wastes may be used for energy recovery as fuel [3]. The TGA at a heating rate of 60°C/min indicates that devolatilization starts at around 250°C and is completed at around 450°C. The maximum rate of devolatilisation takes place between the temperature of 300 and 400°C [3]. Thus, the conversion of these biomass solid wastes into liquid product by fluidised bed pyrolysis method may be considered as a promising option. The pyrolytic oil is of moderate heating value; is easily transported, can be burnt directly in the thermal power plant;

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can possibly be injected into the flow of a conventional petroleum refinery, burnt in a gas turbine or upgraded to obtain light hydrocarbons for transport fuel [4, 5]. Recently some work has been carried out with the biomass solid wastes as feedstock at the Heat Engine Laboratory of Mechanical Engineering Department of Bangladesh Institute of Technology (BIT), Rajshahi to obtain liquid fuel using fluidized bed pyrolysis technology.

## 2.0 MATERIALS

The rice-straw and jute-stick were collected locally in Rajshahi and the bagasse was collected from Rajshahi Sugar Mills Limited, Horian, Bangladesh. The biomass solid wastes were ground and sieved to the size of 300 – 1180  $\mu\text{m}$  and finally oven dried for 24 hours at 110°C prior to pyrolysis. The bulk density and gross calorific value of the solid biomass are presented in Table 1 and proximate analysis and ultimate analysis of the solid biomass are presented in Table 2.

**Table 1** Bulk density and gross calorific value of the solid biomass

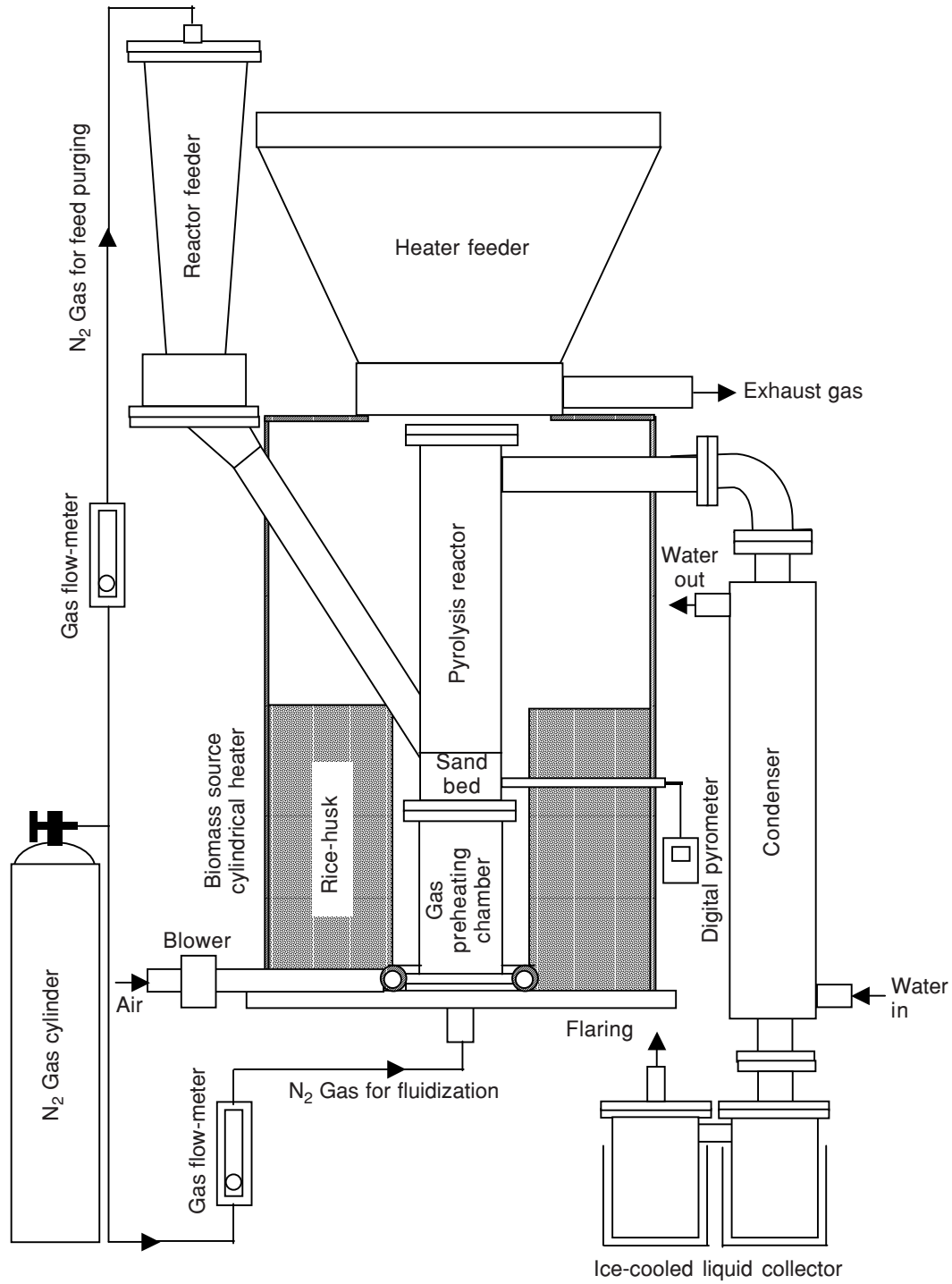
	<b>Rice-straw</b>	<b>Jute-stick</b>	<b>Bagasse</b>
Bulk density ( $\text{kg/m}^3$ )	223.47	178.84	177.08
Gross calorific value (MJ/kg)	14.77	17.32	16.81

**Table 2** Proximate and ultimate analysis of the solid biomass

<b>Proximate analysis</b>				<b>Ultimate analysis</b>			
<b>Contents</b>	<b>Rice-straw</b>	<b>Jute-stick</b>	<b>Bagasse</b>	<b>Elements</b>	<b>Rice-straw</b>	<b>Jute-stick</b>	<b>Bagasse</b>
Volatile	64.45	78.40	74.98	C	41.48	44.94	43.77
Fixed carbon	12.67	11.80	13.57	H	3.60	4.38	6.83
Moisture	9.47	9.02	9.51	N	–	–	–
Ash	13.41	0.78	1.94	O	41.51	49.90	47.46
				S	–	–	–

## 3.0 EXPERIMENTAL SET-UP

The experimental system was a fluidized bed pyrolysis unit. Nitrogen gas was used the as fluidizing gas that made the system inert and dry silica sand as bed material. The sand in the fluidized bed was of mean size 181  $\mu\text{m}$  in diameter with a static bed height of 5 cm. Figure 1 shows the schematic diagram of the pyrolysis conversion



**Figure 1** Schematic diagram of fluidized bed pyrolysis system

system. The reactor was 7 cm diameter  $\times$  37.5 cm high, constructed of stainless steel with full gas flow and temperature control. The reactor was heated externally. The incoming fluidizing nitrogen gas was preheated before entering the reactor in a preheating chamber. The fluidizing gas flow rate was measured and controlled by a gas flow-meter. The reactor bed and gas-preheating chamber were heated by means of renewable biomass energy source cylindrical heater. A blower supplied air required for burning biomass in the heater. By varying the air supply will control the temperature of the reactor. The temperature in the fluidized bed reactor was measured by a digital pyrometer. The gravity feed type heater feeder supplied the heater biomass required for continuous heating of the reactor. The ash of burned biomass in the heater was disposed off through the ash disposal system situated at the bottom of the heater. The exhaust gases which are products of the heater biomass were exhausted to the atmosphere through a pipeline at the top of the heater. The biomass solid waste particles were fed into the reactor by a gravity feed type reactor feeder. The feed rate was maintained almost constant by a feed control valve at the bottom of the reactor feeder. The system was maintained at a pressure slightly above atmosphere by a nitrogen gas pressure regulator. The char was collected from the reactor after completing a run. The vapors and gases were passed through a water-cooled condenser to a series of two ice-cooled collectors to trap the derived liquid product. The fluidizing gas and noncondensable vapor were flared to atmosphere.

#### **4.0 DETERMINATION OF FUEL PROPERTIES OF THE PYROLYTIC OILS USING ANALYTICAL METHODS**

##### **4.1 Physical Property Analysis**

The pyrolytic oils obtained at the maximum liquid yield condition were characterised for their physical properties. These properties were determined according to the standard formulated by the American Society for Testing of Materials (ASTM) and Institute of Petroleum (IP) test methods. The properties determined were: kinematic viscosity, density, pH value, flash point, pour point and gross calorific value.

##### **4.1.1 Kinematic viscosity**

Kinematic viscosity is a measure of the resistance to gravity flow of a fluid. Viscosity of a liquid is an important property since it affects the flow of the liquid through pipelines. The lower the viscosity of the oil, the easier it is to pump and to atomise and achieve finer droplets. The pyrolytic liquid viscosity is highly variable from one liquid to another depending on the water content, production conditions and whether it is the whole pyrolysis liquid or a recovered fraction. This is the major criterion upon which the oils are graded. The kinematic viscosity of the pyrolysis oils was determined

using Glass Capillary Kinematic Viscometer, according to ASTM D445/IP 71 test method [6, 7].

#### 4.1.2 *Density*

The density of an oil is a measure of its aromaticity in hydrocarbon oils, but not in biomass derived oils. It is a necessary parameters used to calculate the volumetric output of pumps and injectors needed to supply a given rate of delivered energy, because the heat of combustion is determined on a weight basis. The density of the oxygenated bio-oils is much higher i.e. 1150 to 1300 kg/m<sup>3</sup>, than petroleum derived hydrocarbon oils. Unlike hydrocarbon oils, the higher density of bio-oils refers to the high oxygen content, rather than a high polycyclic aromatic content. Pyrolysis liquid density varies with time, temperature and water content [6]. The bio-oils having relatively higher densities typically have lower water contents [8]. Wood derived pyrolysis liquid has density of typically 1200 kg/m<sup>3</sup> for a water content of 25 wt% at 20°C [6]. The density of the liquid was measured using an analytical (electronic) balance of model 99100-0 and a weighing bottle.

#### 4.1.3 *Ash content*

Ash is the incombustible material, which remains when fuel is burned. Ash is detrimental in combustion processes in which it lowers the calorific value of the fuel. Excessive amounts of ash can cause high wear in pumps and injectors and lead to deposits in combustion equipment. The ash content of the derived liquids was determined according to ASTM D482/IP 4 test method. The liquid sample was burned in an open crucible and the carbonaceous residue was reduced to ash at high temperature of 732°C.

#### 4.1.4 *pH Value*

The pH value measures the acidity of the derived oil and therefore, indicates the corrosiveness of the oil. Biomass-derived oils are known to be highly acidic. The unusual aspect of bio-oils is their carboxylic acid content, e.g. formic and acetic acids, which causes the oils to have a pH of between 2 and 3 (similar to vinegar). This acidity causes the pyrolysis oils to be corrosive to mild steel, aluminum, etc. Aldehydes also contribute to the low pH. A pH probe with digital meter, of model 3051, JENWAY was used to determine the pH value.

#### 4.1.5 *Flash point*

Flash point is a measure of the liquid temperature necessary for the vapors above a pool of the fuel to ignite by passing a flame through the vapors. This is also a measure

of the volatility of the oil, as well as its ease of ignition. The higher this number, the safer the oil are to handle because the risk of accidental vapor ignition is reduced. The flash point of the liquids was determined using Cleveland Open Cup tester, according to ASTM D92/IP 36 test method. Pyrolysis oil often has a reported flash point of between 50°C and over 100°C, reflecting a wide variation in the content of volatiles. However, above temperatures of 70 to 75°C, water vapors from the pyrolysis oils start to disturb the analysis and a reproducible value is difficult to obtain. No other suitable alternative method has been devised [6]. To get a reasonable result, the test was carried out three times for each sample.

#### **4.1.6 Pour point**

The pour point is the lowest temperature at which the liquid is observed to flow under prescribed conditions. This parameter is an indication of the minimum temperature at which the oil can be pumped without heating the storage tank. The typical values for the pour point are -20 to -28°C. The standard test methods for determination of the pour point are ASTM D97/IP 15.

#### **4.1.7 Gross calorific value**

The gross calorific value is a measure of the quantity of heat released in total combustion and therefore, measures the energy content of a fuel. It is the most important fuel property of any liquid fuel. The gross calorific value of the derived oils was determined using a Parr adiabatic bomb calorimeter according to the test method of DIN 51900 [6, 7]. The high water content pyrolysis liquids can lead to poor ignition and a fine cotton thread is often used as a wick. The heat content of the thread is subtracted from the result. The lower heating value is calculated from the gross calorific value knowing the hydrogen content in the liquids. The typical lower heating value for the fast pyrolysis liquids are in the range of 12.8 to 17.8 MJ/kg.

### **4.2 Elemental Analysis**

The elemental analysis of the oil is an important criterion for the design of a combustion plant utilizing the oil. With the help of the elemental analysis, the combustion calculation can be carried out from which the quantities of combustion air and flue gas and also the composition of the flue gas can be determined [9]. Bio-crude oils have some properties that are quite different from those of petroleum-derived oils. Bio-crude oils contain a large amount of oxygen. The oxygen content of bio-oils (excluding water) is a function of the oxygenated feedstock from which they are made, as well as the residence time and temperature of the pyrolysis step. The sulfur content of bio-oils is naturally low, due to the low sulfur content of biomass. This low sulfur content is one of the positive aspects of bio-oils. The amount of sulfur in the derived oils indicates the

quantity of the hazardous SO<sub>2</sub> emission in combustion processes. One of the variables with bio-oils the nitrogen content of the oil, which reflects the variable protein content possible with biomass. Biomass which has a significant content of green, living plant cells (e.g. green grasses) may have a higher nitrogen content than biomass having a large content of dead plant cells (e.g. straw and wood). The nitrogen content in the bio-oils contributes to NO<sub>x</sub> emissions.

The elemental composition by ultimate analysis, in terms of carbon, hydrogen, nitrogen, oxygen and sulfur (CHNOS) content of the product liquids was carried out by an Elemental Analyzer of model EA 1108 according to the ASTM D3176-84 standard test procedures. The technique used for the determination of CHNS was based on the quantitative "dynamic flash combustion" method. In this method, less than 100 mg of sample was held in a tin container, placed inside the auto sampler drum where they were purged with a continuous flow of helium and then dropped at preset intervals into a vertical quartz tube maintained at 1020°C (combustion reactor). When the sample was dropped inside the furnace, the helium stream was temporarily enriched with pure oxygen and the sample and its container melted and the tin promoted a violent reaction (flash combustion) in a temporary enriched atmosphere of oxygen. Under these favorable conditions even thermally resistant substances were completely oxidised. The quantitative combustion was then achieved by passing the mixture of gases over a catalyst layer. The mixture plug of combustion gases was then passed over copper to remove the excess of oxygen and to reduce the nitrogen oxides to elemental nitrogen. The resulting mixture was directed to the chromatographic column (porapak Q<sub>S</sub>) where the individual components were separated and eluted as nitrogen (N<sub>2</sub>), carbon dioxide (CO<sub>2</sub>), water and sulfur dioxide (SO<sub>2</sub>) with the help of a thermal conductivity detector (TCD) which gave an output signal proportional to the concentration of the individual components of the mixture. Then the signal fed a potentiometric recorder or an integrator or the automatic workstation known as *EAGER 200*. The instrument was calibrated with the analysis of standard compounds using the K factors calculation. Thus, a computer connected to the system from the recording obtained the weight percentage of total weight for each of four components (CHNS). The oxygen content was determined by difference, knowing the ash content.

### 4.3 Compositional Analysis

The functional groups of the pyrolysis liquids obtained at optimum pyrolysis conditions were analysed by Fourier Transform InfraRed (FTIR) spectroscopy to identify the basic compositional groups. The FTIR instrument of model SHIMADZU FTIR 8400 was used to produce the ir-spectra of the derived oils. It provided the absorption spectrum in percentage incident intensity, along the wave numbers 4000 to 500 cm. The standard ir-spectra of hydrocarbons were used to identify the functional group of the components of the derived liquids.

## 5.0 RESULTS AND DISCUSSIONS

### 5.1 Product Yields

The experimental investigation reveals that the optimum reaction condition for rice-straw pyrolysis was at 450°C of the reactor bed temperature at 31 L/min fluidizing gas flow rate with feed particle size of 300 – 1180 µm. At this condition the liquid yield was 40 wt% of the solid rice-straw feed. The pyrolytic liquid obtained was 50 wt% of solid jute-stick feed at an optimum reaction condition of 425°C bed temperature, 30 L/min gas flow rate with 420 – 600 µm feed particle size. The optimum reaction condition for the bagasse was at 450°C bed temperature, 30 L/min gas flow rate with 420 – 600 µm feed particle size. The maximum liquid yield was of 48 wt% of solid bagasse feed.

In general, three products were recovered after each run. From the two liquid collectors, a fairly fluid, oily organic liquid was obtained. The liquid yields were high showing the potential of recovering liquid hydrocarbon from the fast pyrolysis of solid wastes. The liquid appeared brownish dark with a strong acrid smell. Careful handling of the liquid was required since the liquid reacted easily with human skins, leaving permanent yellowish brown marks and an acrid smell for a few days, which cannot be removed by detergent. No phase separation was found to take place. Heavy condensate or tar was also formed and adhered to the inner wall of condenser, liquid collectors and connecting pipes. The tar, which was very viscous at room temperature, could be easily removed from the steel surfaces by detergent and hot water. The char was collected from the reactor. This char was expected to be very reactive, and precautions were required to ensure that it would not be exposed to air when still hot. The gas was diluted by the large flow rate of nitrogen inert gas and flared into atmosphere.

### 5.2 Characteristics of Pyrolytic Oils

#### 5.2.1 Physical and chemical characteristics

Biomass pyrolysis oils are not standardised products and they can exhibit a wide range of properties and composition, according to the feedstock and pyrolysis technique employed. However, Solantausta *et al.* [9] listed the common features of fast pyrolysis biomass liquids, which are usually high in density (approximately 1.2 kg/L), very acidic (pH value 2.8 – 3.8), high water content (15 – 30 wt%), moderate heating value (14 – 18.5 MJ/kg gross calorific value on wet basis) and elemental composition close to those of the feedstock. Bridgwater and Bridge [11] reported that, fast pyrolysis process fed with a dried material with low water content would usually give a single homogenous product with no phase separation. The characteristics of the oils derived from rice-straw, jute-stick and bagasse are very similar to the characteristics of the other biomass pyrolysis oils. The most prominent characteristic is the acidic nature of the oil due to high oxygen content. A low pH value of less than 3 is a common feature



**Table 3** The elemental composition and physical characteristics of biomass pyrolysis oil and its comparison

Analysis	Rice-straw*	Jute-stick*	Bagasse*	Wood waste* [12]	Diesel [12]
Elemental (wt%)					
C	42.30	47.18	46.27	46.24	86.58
H	6.53	8.36	6.55	7.55	13.29
N	Not detectable	Not detectable	Not detectable	0.141	65 ppm
S	Not detectable	Not detectable	Not detectable	0.03	0.11
Ash	0.21	0.33	0.24	0.04	0.00
O	50.96	44.13	46.94	46.00	0.01
Kinematic viscosity @ 30°C (cSt)	10.81	12.08	15.46	66.99 <sup>#</sup>	2.61 <sup>§</sup>
Density (kg/m <sup>3</sup> )	1153.40	1224.70	1198.10	1180.20 <sup>#</sup>	827.1
pH value	3.01	2.92	2.75	2.8	–
Flash point (°C)	103	>70	105	59	53
Pour point (°C)	-8	-14	-24	–	–
Gross calorific value (MJ/kg)	18.340	21.091	20.072	19.800	45.180

\*@ wet oil basis; # @ 40°C; § @ 20°C

in biomass derived liquids and they are therefore, very corrosive. They have also reported that biomass pyrolysis liquid usually has a heating value a little above the biomass feed. Table 3 shows the characteristic of the rice-straw, jute-stick and bagasse pyrolysis oils in comparison to other biomass pyrolysis oil and petroleum product. No sulfur was found and the ash content was found to be less than 0.33% of the oil weight. The nitrogen was not detectable in the pyrolytic oils.

### 5.2.2 Compositional analysis

From the result of Fourier transform infra-red spectroscopy of the derived pyrolytic oils, the FTIR functional groups and the indicated compositions of the liquid products are presented in Table 4. The broad absorbance peak of O-H stretching vibration between 3600 and 3200 cm<sup>-1</sup> indicated the presence of water impurities and other polymeric O-H in the oils. The strong absorbance peak of C-H vibrations between 3050 and 2800 cm<sup>-1</sup> and the C-H of deformation vibrations between 1490 and 1325 cm<sup>-1</sup> indicated the presence of alkanes. The absorbance peaks between 1775 and

**Table 4** FTIR functional groups and the indicated compounds of biomass pyrolysis oil

Frequency range (cm <sup>-1</sup> )	Groups	Class of compounds
3600 – 3200	O–H stretching	Polymeric O–H, water impurities
3050 – 2800	C–H stretching	Alkanes
1775 – 1650	C=O stretching	Ketones, Aldehydes, Carboxylic acids
1680 – 1575	C=C stretching	Alkenes
1550 – 1475	–NO <sub>2</sub> stretching	Nitrogenous compounds
1490 – 1325	C–H bending	Alkanes
1300 – 950	C–O stretching, O–H bending	Primary, secondary and tertiary alcohols, phenol, esters, ethers.
900 – 650		Aromatic compounds

1650 cm<sup>-1</sup> represented the C=O stretching vibration, indicating the presence of ketones, aldehydes and carboxylic acids. The possible presence of alkenes were indicated by the absorbance peaks between 1680 and 1575 cm<sup>-1</sup> representing C=C stretching vibrations. The sharp but less prominent absorbance peaks between 1550 and 1475 cm<sup>-1</sup> represented –NO<sub>2</sub> stretching vibration indicated the presence of small nitrogenous compounds. The overlapping peaks between 1300 and 950 cm<sup>-1</sup> were due to the presence of primary, secondary and tertiary alcohols, ethers and esters due to the C–O stretching and O–H deformation vibration of these functional groups. The absorbance peaks between 900 and 650 cm<sup>-1</sup> indicated the possible presence of single, polycyclic and substituted aromatics groups. These functional groups and the indicated composition have been identified in the pyrolytic derived oils from palm shell and rice-husk from fluidized bed reactor by Ani and Islam [12].

The pronounced oxygenated functional groups of O–H; C=O; C–O and aromatic compounds showed that the oil were highly oxygenated and therefore, very acidic, as have also been indicated by the elemental composition and the pH value. The high fraction of oxygenated compounds reduces the calorific value of the oil since C=O bonds do not release energy during combustion. The presence of hydrocarbon groups C–H; C=C; and alcohols indicate that the liquids have a potential to be used as fuel.

### 5.3 Precautionary Measures to Avoid Errors

To find out the optimum reaction condition for each of the feedstocks, the experiment was carried out taking into consideration three operating variables. They were the reactor bed temperature, gas flow rate and feed particle size. The reactor bed temperature was varied between 400 – 500°C at an interval of 25°C while the fluidizing

gas flow rate was varied between 22 – 39 L/min at an interval of 4 L/min for five different feed particle size. The experiment was repeated three times at every operating point and the optimum reaction condition that gave the maximum liquid yield for each feedstock was identified. The pyrolysis oil obtained from the optimum reaction condition was characterised. Previous studies showed that the optimum liquid yield conditions produced the best quality of liquid. Precautionary measure was also taken into consideration during the determination of each physical property repeating the analysis three times.

#### 5.4 Stability

The stability of pyrolysis oil is a major concern. The biomass solid wastes pyrolysis liquids are relatively unstable with a unique range of properties which are not found in conventional petroleum-derived fuels. It is known that the properties of oil will change when stored for a long time, even at ambient temperature. Pyrolysis oils are chemically reactive with themselves and will polymerize with time, usually with the formation of additional water as a byproduct of the reactions [7]. After prolonged storage, the oil tends to increase their molecular weight owing to chemical reactions, viscosity and also the tendency to separate into a thin oil phase and a thick tar phase. It is very important that the pyrolysis oils be used prior to this phase separation. Therefore, it is essential to analyse the oil immediately after production or stored in an airtight, cold and dark environment before the characterisation.

#### 5.5 Economics of Biomass Pyrolysis Oils

The traditional method of economic evaluation requires capital cost, operating cost and product selling price to be estimated. From this information, the pay-back period, the return on investment and the net present value can be calculated. The production cost per kilogramme of pyrolysis oil obtained from the fluidized bed fast pyrolysis (FBFP) process was used to evaluate the viability of the process. The production cost was determined by estimating the capital and the operating costs.

##### 5.5.1 Capital costs

The capital cost for the plant was determined by summing the costs related to the major pieces of base equipment. The base equipment costs were then multiplied by a direct-cost factor, a building factor, a site improvement factor, and a utilities factor to obtain the total cost for a piece of equipment. The direct cost factor used for this study was taken to have an average value of 1.1. The factors used for the required buildings, site improvements, and utilities were taken to be 1.3, 1.25 and 1.4 respectively [13]. This was then multiplied by an indirect-cost factor of 1.3 to account for the fabrication and installation costs and the design and engineering costs. The resulting figure

provided the Fixed Capital Investment (FCI). The Total Capital Requirement (TCR) for a plant was determined by adding to the FCI, the start-up costs (10% of FCI) and the working capital (5% of FCI). It is worth mentioning that the costs of land and contingencies were not included in the cost estimate. Annualised Capital Cost (ACC) was determined by the formula

$$ACC = \frac{C}{\left\{-(1+I)^{-N}\right\}} \times I$$

where,  $C$  is the capital cost;  $I$  is the interest rate and  $N$  is the plant life time.

### 5.5.2 Operating costs

Majority of the fixed operating costs (maintenance labour, maintenance materials, overheads and insurance) were based on percentages of the FCI. These percentages and the basis for the variable operating costs (feedstock, heater biomass and nitrogen gas costs) are discussed in section 5.5.3. The capital charges in the form of ACC were added to the fixed and variable operating costs to determine the total production cost of the product for the plant. Afterwards, the technical data of product yields were used to determine the Unit Production Cost (UPC) of pyrolysis liquid.

### 5.5.3 Bases of assessment and unit production cost

Table 5 shows the assumptions and costs of the various parameters used to determine production costs. The feedstock used were rice-straw, jute-stick and bagasse that were dried prior to pyrolysis to reduce the water content of the pyrolysis oil. It was assumed that the pyrolysis gas obtained from the process was used for this drying purpose. The feedstock preparation cost was not taken into consideration in the analysis. It was assumed that the cost for disposal of the waste would be credited for the preparation of the feedstock for the process. In this bench-scale unit, the fluidizing gas cost and operating labour cost appeared to be the dominating cost items affecting the unit production cost. These two costs are about 64% and 18% of total production cost. In case of large-scale units, pyrolysis product gases may be recycled as fluidizing gas, in which case a minimal amount of that nitrogen gas cost may be required. Operating labour cost can be reduced in large-scale unit. From the study of Islam and Ani [13] it is found that the unit production cost of rice-husk pyrolysis oil for three different-scale plants of capacity 0.3, 100 and 1000 kg/h are 18.73, 0.38 and 0.18 US\$/kg respectively. The unit production cost in the present bench-scale unit is 5.88, 4.61 and 4.80 US\$/kg for rice-straw, jute-stick and bagasse pyrolysis oil respectively. If fluidizing nitrogen gas is recycled and cost for the gas is avoided then unit production cost is to be 1.7 US\$ for jute-stick pyrolysis oil.

**Table 5** Parameters used in cost bases

Parameters	Values
Plant capacity	0.6 kg/h
Location; time; currency	Bangladesh; 2002; TK.
Plant life	15 years
Annual operating time	1560 h @ 5 h/day
Maintenance labour	1% of FCI
Maintenance materials	3% of FCI
Overheads	2% of FCI
Insurance	2% of FCI
Other fixed operating costs	1% of FCI
Interest rate	10%
Labour rate	75 TK/day
Number of labor	1
Feedstock cost	225, 500 and 250 TK/M.ton for rice-straw, jute-stick and bagasse respectively.
Nitrogen gas price	184 TK per cylinder of 6.3m <sup>3</sup>
Rice-husk price	250 TK/M.ton

## 6.0 CONCLUSIONS

The pyrolytic oils were single-phase liquid products of brownish dark color with acrid smell. The elemental composition of the oils was better than that of solid biomass wastes. The hazardous product creating agents sulfur and nitrogen were not detected in the oils. FTIR analysis showed that the liquids were dominant with oxygenated species. Hence, it is important to deoxygenate the liquids by some upgrading technology. The physical properties analysis showed that the oils were heavy and acidic in nature with moderate viscosity. The oils possessed favorable pour and flash points. The heating values of the oils were moderate, however, the values are similar to other biomass derived pyrolytic oils. These values were significantly higher than that of solid biomass wastes. From this study it is found that the pyrolysis of solid wastes such as jute-stick, bagasse and rice-straw may be a future potential alternative source of liquid hydrocarbon fuels. Further characterisation studies on pyrolysis liquid products from the solid wastes should be conducted to provide ways of utilizing the liquid as fuels in boiler, internal combustion engines etc. or as value added chemicals. The data on the stability and consistency of the liquid, the combustion characteristics

**Table 6** Summary of production cost for rice-straw, jute-stick and bagasse pyrolysis-base case in TK

<b>Cost items</b>	<b>rice-straw</b>	<b>jute-stick</b>	<b>bagasse</b>
Base equipment cost	31,000	31,000	31,000
Fixed capital investment	1 00850	1 00850	1 00850
Total capital requirement	1 15,977	1 15,977	1 15,977
Annualized capital cost	13,260	13,260	13,260
Variable operating cost:			
Feedstock cost	210	468	234
Rice-husk cost	1365 @ 3.5 kg/h	1365 @ 3.5 kg/h	1365 @ 3.5 kg/h
Nitrogen gas	84745 @ 31 L/min.	82012 @ 30 L/min.	82012 @ 30 L/min.
Fixed operating cost:			
Operating labour	23400	23400	23400
Maintenance labour + maintenance materials + overheads + insurance + other fixed operating costs	9076	9076	9076
Total operating cost	1 18,796	1 16,321	1 16,087
Total production cost of pyrolysis oil	1 32,056	1 29,581	1 29,347

etc. are important for the direct utilisation of the liquid as fuel. Catalytic upgrading of the liquid product to higher utility fuels, using various types of catalyst may also be studied.

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