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Solar thermal pyrolysis of non-edible seeds to biofuels and their feasibility assessment

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ABSTRACT

The present study is focused on conversion of non-edible Jatropha seeds biomass to biofuels i.e., liquid, solid and gaseous fuels via solar thermochemical pyrolysis process. All the three products namely; (i) bio-oil (liquid) (ii) biochar (solid) and (iii) pyrolytic gas were characterized by means of TG (Thermo-gravimetric), FTIR (Fourier transform infrared), GC–MS (Gas chromatography mass spectroscopy), proximate and ultimate analysis; and assessed their feasibility as fuel candidates. It is explored that 20% maximum bio-oil yield was obtained with the average reactor temperature of 250–320 °C. The pyrolytic zone for the biomass was identified in the range of 203–508 °C. The ultimate analysis of the bio-oil revealed that the oil is rich in carbon (58.3%) and hydrogen (8.7%) with an average chemical composition of $CH_{1.79}N_{0.05}O_{0.40}$. Relatively lower oxygen content in the bio-oil favors for high heating value. Higher H/C ratio (1.79) and lower O/C ratio (0.4) of the bio-oil indicates its suitability as petroleum fuel for engine applications. The carbon compounds present in the bio-oil are from C7 to C28 which may represent the mixture of diesel and gasoline fuels. Finally, it is emerged from the study that all the three products are exibiting various favorable conditions to be employed as fuel candidates for different applications such as engines and boilers.

1. Introduction

Developing nations like India are highly reliant on renewable energy sources including solar for rapid and sustainable growth. As per the report (April 2017) of Solar Energy Corporation of India (SECI), the country's solar grid had a cumulative capacity of 12.28 GW requirement of solar energy and it has quadrupled its solar-generation capacity from 2.65 GW in 2014 to 12.28 GW in 2017 [1,2]. Pyrolysis is one of the emerging technologies for conversion of waste biomass to energy by solar thermal resources. Pyrolysis of biomass usually produces solid, liquid and gaseous products i.e., biochar (solid), bio-oil (liquid) and pyrolytic gas. Among the three products, bio-oil is having high energy density; hence researchers have been focused on production, up-gradation and utilization aspects of bio-oils tremendously. Composition of pyrolysed bio-oils typically depends on its kind of feedstock and process operating conditions. Research studies have been conducted on pyrolysis of various biomass feedstocks such as Mahua biomass, Karanja biomass, Cotton seeds, Mangaba seeds, Beech wood, Orange-peel and Natural algae [3–12]. It is evident from the literature that pyrolysis may convert more than 50% of biomass content into bio-oils [8,9,13,14]. For example, Pradhan et al. pyrolysed Mahua seeds biomass in a stainless steel semi-reactor at 525 °C temperature using electrical energy source and obtained a maximum yield of 49% bio-oil along with 18% biochar [3]. Similarly, Seal et al. obtained the bio-oil yield of 58.6% from Cotton seeds biomass at 550 °C using electrical energy source [8]. Nayan et al. reported bio-oil yield about 57% from Karanja seeds biomass at 500 °C [7]. Some researchers worked with other feedstocks such as algae, plastics wastes and de-oiled cake for pyrolysis and achieved significant bio-oil yields [9,10,12]. At other hand, in some investigations, researchers obtained low pyrolysed bio-oil yields. For example, Hossain et al. achieved only 9% bio-oil yield along with 79% biochar with the pyrolysis of de-inking sludge pellets in a Pyro-former auger type reactor [5,15]. The reasons for lower oil yield could be due to type of reactor used, quality/type of feedstock used, variation in operating temperature, and other process operating parameters.

It is well known that pyrolysis of biomass is an endothermic reaction that takes place at an operating temperatures about 300–700 °C [16]. To attain these temperatures in conventional pyrolysis technology, heat energy is usually supplied from electrical energy sources [4,9,17–22] that have deleterious effects on energy efficiency and the environment.

Abbreviations: C, carbon; C_2H_6, ethane; CH_4, methane; CO, carbon monoxide; CO_2, carbon dioxide; DTG, differential thermo-gravimetric analysis; FITR, Fourier transform infrared; GC–MS, gas chromatography–mass spectrometry; H, hydrogen; H_2, hydrogen molecule; N, nitrogen; O, oxygen; S, sulphur; TGA, thermo-gravimetric analysis

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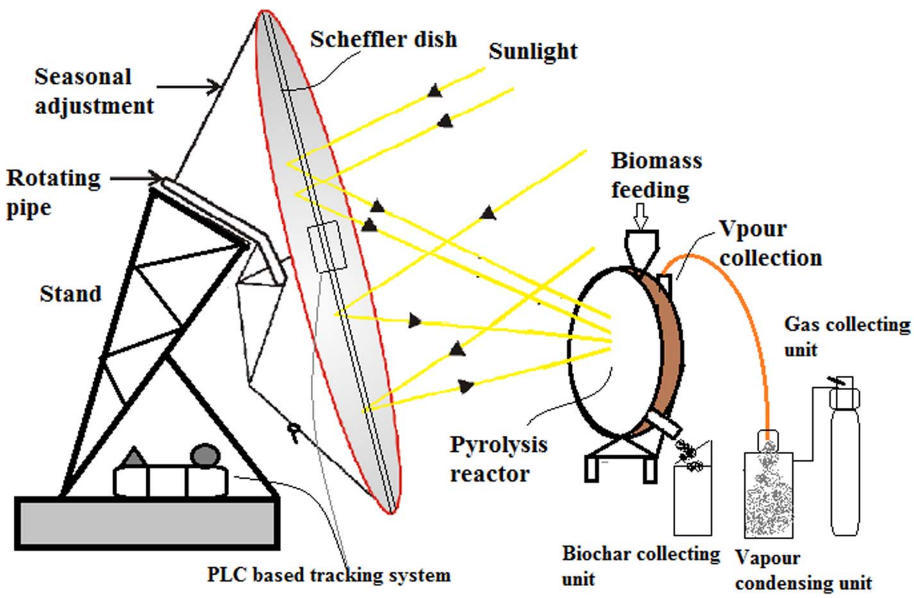

Fig. 1. Schematic diagram of Integrated Scheffler dish and pyrolysis reactor.

This problem could be resolved by replacing electrical energy with solar thermal energy [14,23–25]. Solar thermal pyrolysis is one of the potential options for production of the high energy density fuels [16]. Solar thermal pyrolysis is having unique advantages over traditional methods due to its renewable in nature and cost competitiveness. Beatie et al. have done a pioneering work in the field of solar thermal pyrolysis, and produced pyrolysed gas as a main product [26]. They performed solar thermal pyrolysis of coal and obtained the maximum gas yield of 31 mmol/g coal at a flux level of 1 MW/m^2 [26]. In continuation, Zeng et al. have contributed enormously in solar thermal pyrolysis of Beech wood biomass using transparent Pyrex balloon reactor at laboratory scale [24,27–33]. They also carried out numerical and computational fluid dynamics (CFD) simulation works on the pyrolysis processes and product yield optimization [23,34]. They studied the effect of operating temperature and gaseous medium flow rate on the yield of pyrolysis products. Solar pyrolysis reactor temperature was varied from 600 to 2000 °C, and argon flow rate was varied from 3 to 12 Nl/min [23]. Morales et al. investigated on pyrolysis of orange-peels biomass using a parabolic-trough solar concentrator [14]. The solar pyrolytic reactor achieved 465 °C at middle of the focal line and obtained 77.64 wt% bio-oil, 20.93 wt% biochar and 1.43 wt% non-condensable gas.

It is important to mention that composition of pyrolysed oil is highly dependent on the type of feedstock and process operating conditions. It is understood that pyrolysed bio-oil consist of more than 300 organic compounds and generally have a mixture of aliphatic hydrocarbon, alcohols, aldehydes, ketones, furan, amide, fatty acids, aromatics, esters, ethers and phenols derivatives [35,36]. Main species of pyrolysed bio-oil are C (carbon), H (hydrogen), N (nitrogen), S (Sulphur) and O (oxygen). Presence of C, H and O elements in pyrolysed bio-oils would play a major role in combustion properties of the fuel-air mixtures. Carbon content in pyrolysed oils is generally lower than diesel fuels [37]. It varies from 40 to 80% depending on pyrolysis technology, feedstock composition and reaction temperature [15,24,35,37]. Hydrogen content in the bio-oils varies from 4 to 12% depending upon the pyrolysis process conditions. The oxygen content in the bio-oils may reach up to 50% which is higher than diesel and biodiesel fuels [29,31]. The disadvantage of high oxygen content in pyrolysed bio-oils is lower calorific value [36]. It was observed from the literature review that many studies were conducted on the assessment of bio-oils, but the information on assessment of entire pyrolysed products (liquid, solid and gaseous products) as a holistic approach is scanty. Hence, to have a proper insight on the entire pyrolysed products and their feasibility to use as fuel candidates in various applications, the present study was aimed to pyrolyze a locally available biomass i.e., Jatropha seeds using concentrated solar energy. Solar thermochemical pyrolysis was carried out in a batch scale (10 kg biomass) to obtain the pyrolysed products namely bio-oil, biochar, and pyrolytic gas. Novelty of the study includes; (i) characterization assessment of entire spectrum of pyrolysed products i.e., bio-oil, bio char, and pyrolytic gas (ii) pyrolysis of locally available Jatropha seeds biomass (iii) use of renewable solar energy source instead of conventional electrical energy for pyrolysis process (iv) demonstration of solar thermal bio-refinery approach for biofuels production.

2. Methodology of production and characterization of pyrolysed products

2.1. Raw materials

In the present study, Jatropha seeds biomass was used as feedstock for solar thermal pyrolysis process. Jatropha seeds were procured from the local vendor in Dehradun city, India. Jatropha seeds were dried under sun light for 8–10 h to remove moisture content and then converted into powder form using a Screw-press expeller [16]. Subsequently the powder was dried under sun light for 4–5 h and then stored in air tight plastic buckets. The dried biomass was fed into a solar thermal pyrolysis reactor. Detailed information with photographic views on the biomass preparation was mentioned in the Authors' earlier study [16].

2.2. Solar thermal pyrolysis experimental setup

A circular fixed bed type reactor was developed for a batch scale pyrolysis process with the maximum biomass capacity of 15 kg/batch. A 16 m^2 Scheffler parabolic solar dish was developed for focusing the distributed radiation on to the pyrolysis reactor as shown in Figs. 1 and 2. The concentration ratio of the Scheffler dish is 16:1. The schematic diagram of the integrated Scheffler dish and reactor system is shown in Fig. 1. Detailed technical specifications of the Scheffler dish and the reactor are given in Table 1. A program logic control (PLC) based automatic solar tracking system was provided for continuous solar radiation focus on the reactor with reference to changes in the direction of sunlight during day time. Powdered biomass was fed into the pyrolysis reactor by Hooper (Figs. 1 and 2). When the Scheffler dish was focused on to the reactor, temperature of the reactor surface