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Pyrolysis and gasification characteristics of Pongamia residue (de-oiled cake) using thermogravimetry and downdraft gasifier

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HIGHLIGHTS

- Thermal decomposition of the Pongamia de-oiled cake occurs in three stages.
- At low heating rate (10 °C/min), the higher mass loss rate was achieved.
- The minimum activation energy of 162 kJ/mol is required for complete gasification.
- Gasification efficiency of the de-oiled cake pellets was 65% as compared to the wood (84%).
- Pongamia de-oiled cake pellets of 17 mm and 11.5 mm diameter are not suitable for efficient and problem free gasification.

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ABSTRACT

General research in the area of gasification of biomass includes either study of kinetics of pyrolysis or gasification of selected bios mass. A combined kinetic investigation of the pyrolysis of the de-oiled cake at various heating rates along with gasification of pelletized biomass was carried out in the present work. It is found that the thermal decomposition of de-oiled cake occurs in three stages. Most of the material decomposed (~60%) in stage-II between 166 °C and 480 °C. Kinetic parameters were obtained by differential and FWO methods. The activation energies are obtained in the range of 68.8–177.9 kJ/mol and 41.3–161.8 kJ/mol by differential method and FWO methods respectively. These results were consistent with those obtained in the literature. The TGA results show that a minimum heating rate (10 °C/min) and minimum activation energy (162 kJ/mol) is required for pyrolysis and gasification of de-oiled cake. The results of TGA were used to select the suitable size of pellets. De-oiled cake pellets of 17 mm and 11.5 mm diameter and length in the range of 10–68 mm were prepared and gasified in a 20 kWe downdraft wood gasifier. The complete gasification of pellets could not be achieved because of less porosity and more elasticity and presence of larger thermal gradient within the pellets. Pongamia de-oiled cake pellets of 17 mm and 11.5 mm diameters are not suitable for gasification.

1. Introduction

In many developing countries, the fraction of biomass energy consumed ranges from 40% to 50% since the countries have large agriculture and forest area [1]. India, one of the leading developing countries, has huge potential of the biomass resources consisting about 321 million tonnes per year in agro-ecological zones [2]. In different parts of India, forest oilseeds like *Madhuca indica*, *Pongamia pinnata*, *Shorea robusta*, *Mallotusphilip pines*, *Mesua ferra*, *Garcinia indica*, are available with good tree density. Oil from these species is being used for biodiesel production. This biodiesel can be used for generating electricity using diesel engine generators [3&4].

Pongamia pinnata is a forest tree belonging to the family Leguminosae, grown in all parts of India, particularly in Tamil Nadu, Andhra Pradesh and Karnataka, for its ecological advantages. The seed contains 27–39% oil, 20–30% protein and a group of furanoflavonoids that constitute 5–6% by weight of the oil. The estimated production of seed is nearly 0.11 million tonnes per annum in India. The projected production of oil is nearly 30,000 tonnes per annum, at present. The oil is extracted by expellers, leaving 15–20% of residual oil in the cake. The cake, which is bitter and pungent, is used (in small quantity) as manure, fungicide and insecticide. Although the cake is rich in proteins, it is unpalatable and toxic due to the presence of karanjin, pongamol and an unusual amino acid, glabrin. However, raw cake is not normally used as feed for animals

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and livestock due to its toxicity [5]. The Pongamia de-oiled cake, a solid residue that is usually discarded after extraction of oil from the seeds, contains lignin and cellulose in varying ratios. Moreover, due to increasing demand of biodiesel, the quantity of de-oiled cakes has increased tremendously and about 2 tonnes of oil cake is discarded as a waste for every tonne of biodiesel produced. One of the major problems associated with this increase would be the disposal of shells and the de-oiled cake after expelling oil from the seeds [6].

Pyrolysis could be a promising residue management option to convert the waste of shells and de-oiled cake to fuel products that are easier to transport, store, handle, and utilize. Pyrolysis is one example of thermochemical conversion of biomass [7]. However, pyrolysis is an extremely complex process; it generally goes through a series of reactions and can be influenced by many factors. This process yields liquid oil, solid charcoal, and gases in different proportions, depending on the temperature, heating rate, reactor type, and biomass particle size [8–11].

A few major attractions of gasification are that it can convert waste or low-priced fuels, such as biomass, coal, and petcoke, into high-value chemicals. Biomass holds great appeal for industries and businesses; especially in the energy sector [12]. Biomass gasification is the latest generation of biomass energy conversion processes and is being used to improve the efficiency and to reduce the investment costs of biomass electricity generation through the use gas turbine technology [13].

Many types of gasifiers were reported in the past and they can be broadly categorized based on the basis of the flow direction of air/gas in a gasification reactor. The gasifiers are classified as up draught, downdraught and cross-draught gasifiers. In all these gasifiers, biomass flows downwards by gravity. In up draught gasifier, the flow of air and gas is upwards direction. If the flow of air and gas is downwards, it is downdraught gasifier. While in case of a cross-draught gasifier, the air and gas flows horizontally, perpendicular to the flow direction of biomass [14].

Lenis et al. [16] reported a statistical repeatability study of the main biomass gasification process parameters in a laboratory-scale fixed bed downdraft gasifier on batch operation by using analysis of variance. They suggested that the solid fuel distribution inside the bed was always different, leading to variations in the process parameters.

Numerous investigations on different types of biomass species have been carried out in the past on downdraft gasification systems. The briquetted leather residues (nominal size of 70 × 50 mm and bulk density of 537.30 kg/m^3) were successfully gasified in a throated 10 kWe downdraft gasifier. The temperatures of various zones were measured. The oxidation, pyrolysis, and drying zone temperatures were respectively measured around, 1050 °C, 530 °C, and 290 °C. The large briquette sizes of the leather residues occasionally formed bridging in the throat zone of the gasifier [17]. Vera et al. [18] carried out an experimental and modeling study of a downdraft gasifier and gas engine fueled with olive oil industry wastes. The gasifier is fed with olive mill wastes: small branches and leaves and olive pits. The producer gas generated from crushed olive pits has calorific value of 5.1 MJ/kg and 3.7 MJ/kg for small branches and leaves. In this study; they found that an olive pit has good potential for combined heat and power plant. The small branches and leaves may be used in combustion application but not for gasification.

In view of above context, the objective of present work is focused on the study of Pongamia de-oiled cake as an alternative source of energy through pyrolysis and gasification. It is not possible to use de-oiled cake directly in gasifier. The better option is to pelletize the de-oiled cake. The producer gas generated from the pellets can be used for heat and or power generation for rural areas.

2. Experimental setup and methodology

2.1. Feedstock characterization

In the present work, the Pongamia de-oiled cake was collected from the oil processing industry in the state of Madhya Pradesh, India. The Pongamia de-oiled cake was air dried and crushed and sieved to produce the particles with the size less than 297 microns.

The physical and chemical properties (proximate and ultimate analysis) of the Pongamia de-oiled cake are given in Table 1. The de-oiled cake pellets (DOCP) have a higher bulk density (489 kg/m^3) when compared to the Pongamia pure shells (146 kg/m^3). DOCP has slightly higher calorific value and carbon content when compared to the Pongamia shells as shown in Table 1. The important properties of Pongamia shells and DOCP in comparison with wood are listed in Table 1.

2.2. Experimental conditions for pyrolysis

The Perkin–Elmer TGA-7 thermogravimetric analyzer was used to analyze the thermal characteristics of the Pongamia residue (de-oiled cake). The samples of de-oiled cake were pyrolyzed with heating rates of 10, 15, 20 and 30 °C/min respectively in the temperature range (TR) from room temperature to 700 °C. Nitrogen was used as a carrier gas with a flow rate of 20 ml/min throughout the experiment. The thermogravimetric analysis was carried out in order to obtain kinetic parameters of the samples.

2.3. Pelletization of Pongamia de-oiled cake

The pelletization of de-oiled cake was carried out in two steps, namely crushing of raw material and pelletization. A special hammer mill was used for crushing of raw material. An existing hammer mill with 32 numbers of hammers and screen size of 8 mm holes was used to crush the de-oiled cake into fine powder. A mixture of fine powder, water and bonding agent (if required) was prepared for production of pellets. A pelletizing machine with a flat die was used to make the pellets. The flat die has total 33 holes of 18 mm diameter with a working width of 77.5 mm and effective compression length of 45 mm, total thickness 53 mm and has a maximum output of 100 kg per hour. The power consumption of the pelletization machine was measured to be in the range of 6.2–6.9 kW at full load condition.

Another die plate of 12 mm hole diameter was fabricated. All other dimensions of the die plates were the same as the older die plate. The purpose of fabrication of this die plate was to study the effect of hole diameter on the bulk density of pellets, length of pellets, thermal properties of the pellets and quality of the producer gas generated with smaller diameter pellets.

The Pongamia de-oiled cake pellets (DOCP) of 17 mm and 11.5 mm diameters were produced as shown in Figs. 1 and 2 respectively. These pellets were air dried and stored in the 15 kg plastic bags. The bulk density of pellets of 17 mm and 11.5 mm diameters was measured to be 489 kg/m^3 and 502 kg/m^3 respectively. The length of DOCP was in the range of 10–68 mm. The pellets of 17 mm diameter were less porous with very smooth surface finish and relatively more plasticity. The surface finish of pellets of 11.5 mm diameter was rough as compared to the pellets of 17 mm diameter.

The biomass that could be used as the feedstock in the existing downdraft gasifier are different species of wood whose bulk density is above 175 kg/m^3 and ash content is less than 2%. The bulk density of hardwood and softwood are 330 kg/m^3 and 250 kg/m^3 respectively [21].