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Development of Torrefaction Technology for Solid Fuel Using Renewable Biomass

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<http://dx.doi.org/10.5772/intechopen.76100>

Abstract

Fossil fuel sources such as coal, crude oil and natural gas would eventually get exhausted and their price continuously fluctuates. During the past four decades, many researches have tried to find alternate fuel resources to satisfy the worldwide increasing energy demand as well as to minimize dependence on fossil fuels. Among many possible alternate fuel sources, agriculture biomass residues exhibit most promising possibility due to their inherent characteristics in storing solar energy and amenability in subsequent conversion into convenient solid, liquid and gaseous fuels. Torrefaction is a thermal method for the conversion of biomass operating in temperature range of 200–300°C under atmospheric conditions in the absence of oxygen. Agricultural crop residues that are abundant in the Philippines such as coconut leaves, cogongrass and rice husk were utilized to produce solid fuel by torrefaction for use as alternative source of energy. The key torrefaction products were collected and analyzed. Combustion characteristics of both torrefied and untorrefied biomass were investigated. Torrefaction of the biomass significantly improved the heating value, proximate compositions also improved and were comparable to coal and combustion characteristics were superior making it more suitable for fuel applications. The design of the torrefaction process was researched and developed.

Keywords: biomass, renewable energy, torrefaction, cogon grass, rice husk, coconut leaf

1. Introduction

The reserves of non-renewable energy sources (coal, crude oil, natural gas) gradually get exhausted and their price continually increases. Nevertheless, they cover about four-fifth of the energy consumption [1].

In the last four decades, researchers have been focusing on alternate fuel resources to meet the ever increasing energy demand and to avoid dependence on crude oil [2].

Among different sources of renewable energy, biomass residues are the most potential raw material due to their inherent capability to store solar energy and amenability to subsequent conversion to convenient solid, liquid and gaseous fuels. Further, biomass is a renewable source of carbon through a global carbon cycle and can be a source to make many chemicals.

With serious concern about deforestation as one of the causes of global warming, especially in developing countries, and need for reforestation to maintain global ecological balance, increasing demand is being made for proper utilization of agro and forestry biomass residues to play the role previously carried out by wood.

Torrefaction is a recently well-known technology which can change biomass properties to become a higher energy quality biofuel. From a viewpoint of chemical components, torrefaction process comprises mainly the removal of oxygen to yield a final solid product. The torrefied biomass product contains a lower O/C ratio compared to the original raw biomass.

Torrefaction occurs through the heating of biomass below 300°C in the absence of oxygen, where moisture and volatile materials are lost. It was first applied in 1939, then in 1984 but forgotten until recently. Published papers and patents issued were from late 2000s to present. It can convert biomass wastes to solid fuel affordably without complications.

The Philippines is mainly an agricultural country with a land area of 30 million hectares, 47% of which is agricultural. The total area devoted to agricultural crops is 13 million hectares distributed among food grains, food crops and non-food crops. Among the crops grown, rice, coconut and sugarcane are major contributors to biomass energy resources. The most common agricultural residues are rice husk, rice straw, coconut husk, coconut shell and bagasse [3].

In order to utilize agricultural crop residues and to improve its biomass properties, there is a need to create new knowledge and apply it to be more productive focusing on creativity and innovation. Agricultural crop residues that are abundant in the Philippines such as coconut leaves [4, 5], cogongrass [5], and rice husk [5], were utilized to produce solid fuel by torrefaction for use as alternative source of energy. The design of the torrefaction process based on the biomass characteristics was researched and developed.

2. Biomass upgrading as energy source

In future energy supply scheme, biomass can play an important role in supplying renewable energy [6]. Biomass is an attractive energy source as a renewable energy, especially as a sustainable carbon carrier.

2.1. Biomass

Biomass can generally be defined as any hydrocarbon material which mainly consists of carbon, hydrogen, oxygen and nitrogen. Sulfur is also present in less proportion. Biomass resources include many natural and derived materials such as woody and herbaceous species, wood wastes, bagasse, agricultural residues, waste paper, municipal solid wastes, sawdust, biosolids, grass, food wastes, animal wastes, aquatic plants, and algae, etc. Woody materials are preferred among biomass resources because they contain much higher energy value. Most important feature of biomass is its inherent climate neutral behavior. When biomass is grown in a sustainable way, during the life cycle of biomass production and application, no net amount of CO₂ emits into the atmosphere. The CO₂ released during the utilization of biomass is stored in return in the biomass resource through photosynthesis, which means a climate neutral carbon cycle of CO₂. Biomass is considered as an environmentally friendly alternative energy source replacing fossil fuels because it is produced in nature by photosynthesis from CO₂ and H₂O [7].

On the other hand, some biomass properties are inconvenient, particularly its high oxygen content, a low heating value, a hydrophilic nature and high moisture content. Also, the energy accumulation to biomass through photosynthesis has known to be a process of low energy efficiency. The overall energy efficiency from solar energy to biomass energy is 1–3% [8]. Typical disadvantages of biomass are its tenacious and fibrous structure and its heterogeneous composition that makes process design and process control more complicated.

Biomass has unique characteristics that necessitate pre-processing before it can be stored, transported or used in various applications. Unlike fossil fuels which are mined at one location, biomass is often available seasonally in small quantities scattered over many locations [9]. Biomass is highly heterogeneous in quality and nature, and is available in low energy density form [10]. It has relatively high moisture content and consequently lower heating value compared to fossil fuels [11]. It is therefore often needs to be pre-treated to improve handling [12].

2.2. Thermal conversion processes

Burning biomass in an oxidative environment is the oldest conversion process practiced by man. Combustion, however, does not intend to produce value-added products in the form of fuels, chemicals or materials, as other thermochemical conversion technologies, but only heating value [13].

Thermal conversion processes can be categorized into combustion, gasification, pyrolysis and the emerging torrefaction technology according to the operating conditions. The products of the thermochemical processes are divided into a volatile fraction consisting of gases, vapors and tar components and a carbon rich solid residue [4].

3. The torrefaction technology

Torrefaction is a recently well-known technology to upgrade biomass for combustion and gasification applications. It is a thermal pre-treatment technology carried out at atmospheric pressure in the absence of oxygen. Torrefaction of biomass can be described as a mild form of pyrolysis that occurs at temperatures between 200 and 300°C [4]. During torrefaction, the more easily combustible components of biomass (i.e. hemicelluloses) are decomposed first and most vigorously, through carbonization. Only minor decomposition of lignin and cellulose occur at torrefaction temperatures but rate of decomposition depends on the type of biomass [14]. Their chemical structure is changed but no significant mass losses occur [15, 16]. The solid uniform product that is produced has a very low moisture content, high heating value [17] and less hydrophilic compared to the untreated biomass to fresh biomass [1]. Furthermore, the fibrous and tenacious nature of the biomass is reduced, resulting in a brittle material that can easily be comminuted into smaller particles [18].

4. Renewable biomass sources

Like any developing country, the Philippines is facing a formidable challenge of promoting sustainable energy options to support the energy requirements of its economic and social development goals with minimal adverse effects on the environment. The Philippines utilizes renewable energy sources including hydropower, geothermal and solar energy, wind power and biomass resources. In 2015, these sources contributed 20,963 GWh of electrical energy, out of which, 41% is hydropower while 53% is geothermal power. Solar energy, wind power and biomass energy application accounts for around 6% of the primary use in the country. These renewable energy sources represent 25.44% of the country's energy needs [19].

4.1. Coconut leaf, cogongrass and rice husks as a renewable source of energy

Among the coconut farm wastes such as husks, shell, coir dust and coconut leaves, the latter is considered either the most grossly under-utilized or completely un-utilized, only to be utilized by in situ burning at the coconut farm in order to dispose. A study conducted by Banzon [20] considered only the petiole to assess the fuel potential of the coconut leaf. Banzon reported that 376.9 million trees each producing at least 12 leaves a year or a total of 45×10^8 leaves with a total weight of 4000 kcal/kg (16.7 MJ/kg) makes the energy available from the coconut petiole equal to 39×10^{12} kcal [20, 21].

Imperata cylindrical, or cogongrass grows all around the world, including the Philippines. In general, cogongrass is composed of three main components: Cellulose, hemicellulose, and lignin [22]. Cellulose and hemicellulose can be converted into fermentable sugars and produce a large amount of fuels and chemicals by fermentation and chemical processes [23]. *Imperata*

is being considered as a feedstock for bioethanol. Very few studies have reported the use of cogongrass as a renewable energy source.

Agricultural wastes such as rice husks are now used as a source of energy that helps advance the agriculture industry, particularly on rice mechanization and post production operations. The Philippines produces an average of 2 million metric tons of rice husks annually. A kilo of rice husk basically contains about 3000 kcal of heat energy and can provide sufficient amount of clean gaseous fuel when gasified. Converting this available biomass waste into energy by gasification can provide about 25 pJ of energy which can be utilized for various heat and power applications, especially in rice farming and rural-based operations [24].

5. Methodology

5.1. Sample production of biomass

Dried coconut leaves were collected in a coconut farm in Calauan, Laguna (CALABARZON, Region IV-A). Cogongrass and rice husks were collected from Puerto Princesa, Palawan [5]. The dried biomass was air dried and cut into small pieces. The cut biomass was stored in plastic containers at room temperature.

5.2. Characterization of the raw biomass

5.2.1. Thermogravimetric analysis (TGA)

The thermal behaviors of dried coconut leaves [4, 5], cogongrass [5] and rice husks [5] (about 5.769 mg milled using a Thomas Willey mill) were investigated at the Polymer Materials Laboratory at the Institute of Chemistry, College of Science, University of the Philippines, Dilijan, Quezon City using a TGA Q50 (TA Instrument). The heating program consisted on a 5 min hold at 30°C, ramp up to 800°C at a heating rate of 10°C/min, and then the weight difference was recorded as a function of temperature profile. Nitrogen was used as a purging gas at a flow rate of 50 ml/min [4].

5.2.2. Heating value

The calorimetric experiments were performed using the raw and torrefied biomass. About 1 g size sample was placed in a nickel crucible introduced into a Parr 1356 Oxygen Combustion Bomb Calorimeter. The experiments were performed at 25°C. The bomb was filled with oxygen at a filling pressure of 30 atm. The calorimeter was placed in an isothermal-jacket with an air-gap separation of 10 mm between all surfaces. The calorimeter was filled with two liters of de-ionized water. The fuel was ignited through external electric connections. Temperature of this water was measured to 10⁻⁴°C at intervals of 10 s at the start of ignition to calculate the heating value for each sample [4].

5.2.3. Proximate analysis

Samples of the feedstock or raw biomass and the solid product or torrefied biomass were analyzed at the Analytical Services Laboratory at the Institute of Chemistry, U.P. Diliman, QC for moisture content using a micro thermogravimetric analyzer according to Method 925.45 B “Official Methods of Analysis of AOAC International (17th edition Revision 1)” and ash content according to Methods of Analysis of AOAC International (17th edition Revision 1)” and ash content according to method 923.03 Ibid [4].

5.3. The torrefaction reactor

The torrefaction batch reactor was developed and fabricated for the laboratory scale. The reactor which is of rotary drum type (capable of approximately 200–500 g per batch, depending on material) is made of stainless steel with an inside diameter of 20 cm, length of 30 cm and thickness of 1 cm. It consists of (1) an air locked feeder cover where the feedstock is fed; (2) the heating chamber where torrefaction process of the biomass takes place; (3) rotor blades that allows uniform heating of the biomass; (4) the thermometer that displays the temperature in the heating chamber; and (5) a tachometer that measures the rotation speed of the shaft [4]. **Figure 1** shows the schematic diagram of the torrefaction reactor and its parts. **Figure 2** shows the fabricated torrefaction batch reactor.

5.4. The torrefaction experiment

Figure 3 shows the experimental set-up of the torrefaction experiment. Raw biomass was torrefied using the lab-scale torrefaction unit. Four torrefied samples were prepared with different feedstock conditions and different operating temperatures based on the TGA results of the untorrefied (raw) biomass (see **Table 1**).

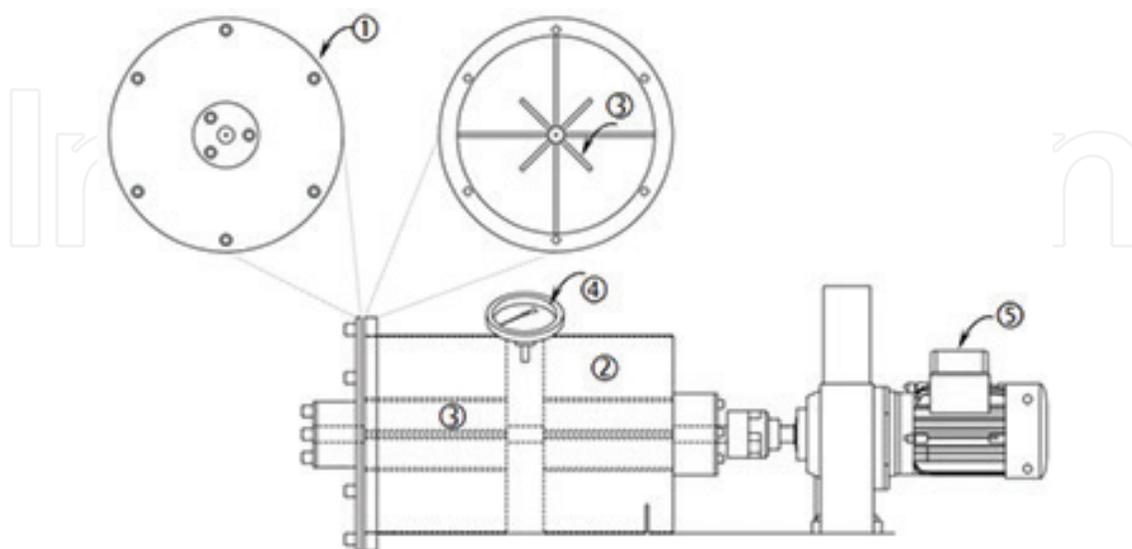


Figure 1. Schematic diagram of torrefaction reactor and its parts.

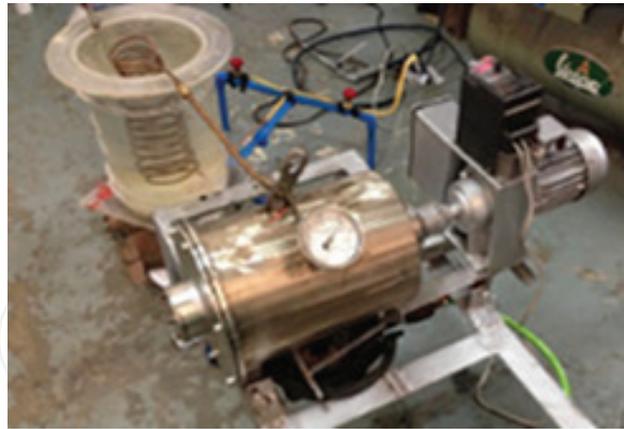


Figure 2. The fabricated torrefaction reactor.

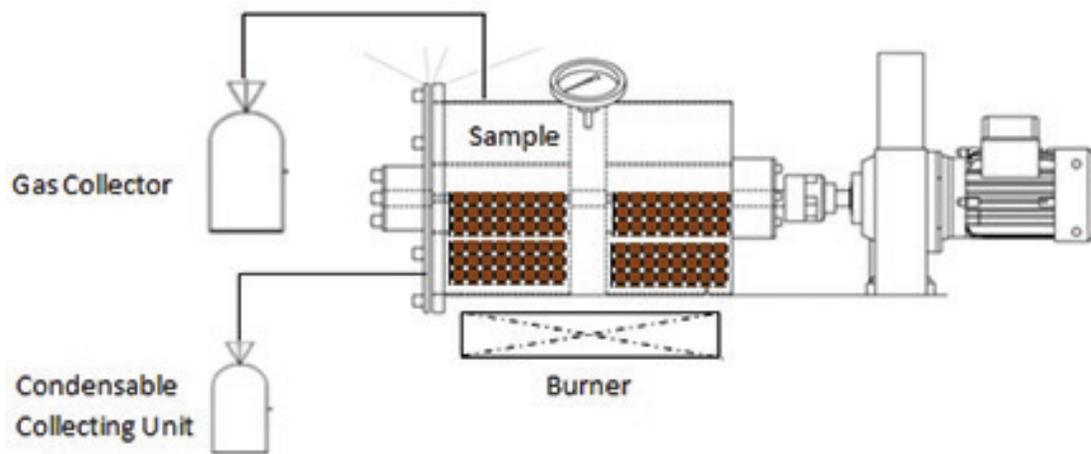


Figure 3. The experimental set-up of the torrefaction experiment.

Property	Coconut leaves	Cogongrass	Rice husk
Operating temperature (°C)	245–290	247–298	238–293

Table 1. Torrefaction operating temperature conditions.

The reactor was heated, at the rotating speed of the shaft of about 23 rpm. When the desired reaction condition was reached, the set-up was allowed to cool, the solid product or the torrefied biomass was weighed. The condensate was collected throughout the process by connecting the condensate collecting unit to a condenser. The volume and weight of the condensate were measured. The collected gas and the condensate were disposed properly. Bomb calorimetry and proximate analysis were used in determining the physical and fuel properties of the torrefied biomass. Fuel characteristics (heating value, moisture content, fixed carbon content, and ash content) of the raw and torrefied biomass were compared. Design engineering principles were used to develop a process design of the production of solid fuel from renewable biomass.

6. Results and discussion

6.1. Characterization of the raw and torrefied biomass

6.1.1. TGA

TGA is very important in the torrefaction of renewable biomass to establish the thermal properties of the dried biomass [4].

The thermogravimetry profile of dried coconut leaves in **Figure 4** shows an onset temperature of 245°C that denotes the temperature at which weight loss begins. Starting from 5.679 g, a weight loss of 7.436% was observed. After which the weight drastically falls down until a temperature of 350°C is reached when a weight loss of 53.33% of its weight was recorded. This is called the first derivative peak temperature, also known as the inflection point. This indicates the point of greatest rate of change on the weight loss curve. It was reported that the higher the cellulosic content of the dried coconut leaves, the higher was the thermal degradation rate and the initial degradation temperature [4].

The TGA results for dried coconut leaves [4, 5], cogongrass [5] and rice husks [5] shown in **Table 1** provided the basis for the optimum operating temperatures (between 245 and 298°C) that were utilized in the torrefaction experiment.

6.1.2. Heating value, proximate analysis

The heating value obtained in a bomb calorimeter test represents the gross heat of combustion for the sample. This is the heat produced when the sample burns, plus the heat given up when the newly formed water vapor condenses and cools to the temperature of the [4].

The results of the experiments showed that torrefaction can improve the fuel properties of the biomass. The fuel characteristics of the raw and torrefied biomass are shown in **Figure 5**. **Figure 5(b)** shows the moisture content was reduced by an average of 67%. The heating values were increased to 20–26 MJ/kg, see **Figure 5(a)**. The fixed carbon was increased to 44–46%, see **Figure 5(d)**. The ash content increased to 9–28%, see **Figure 5(c)**. These values approach that of subbituminous coal that coal contains 42–52% carbon (on a dry, ash-free basis) and has calorific values ranging from about 19 to 26 MJ/kg.

The raw biomass low heating values are due to low fixed carbon content of about 45% and relatively high moisture content, typically about 50% [25]. Torrefaction significantly improved the heating values of the biomass (see **Figure 5a**). Improvement of heating value is due to increased fixed carbon. The fixed carbon content of torrefied biomass is high (25–40% depending on reaction conditions) [12, 15, 26]. The combustion property also improved; torrefied biomass burns longer due to larger percentage of fixed carbon [27]. Torrefaction reduces the O/C ratio and this makes the biomass better suited for gasification [26]. Gasification also produces less smoke during the process since smoke causing volatiles are driven off during torrefaction [28, 29].

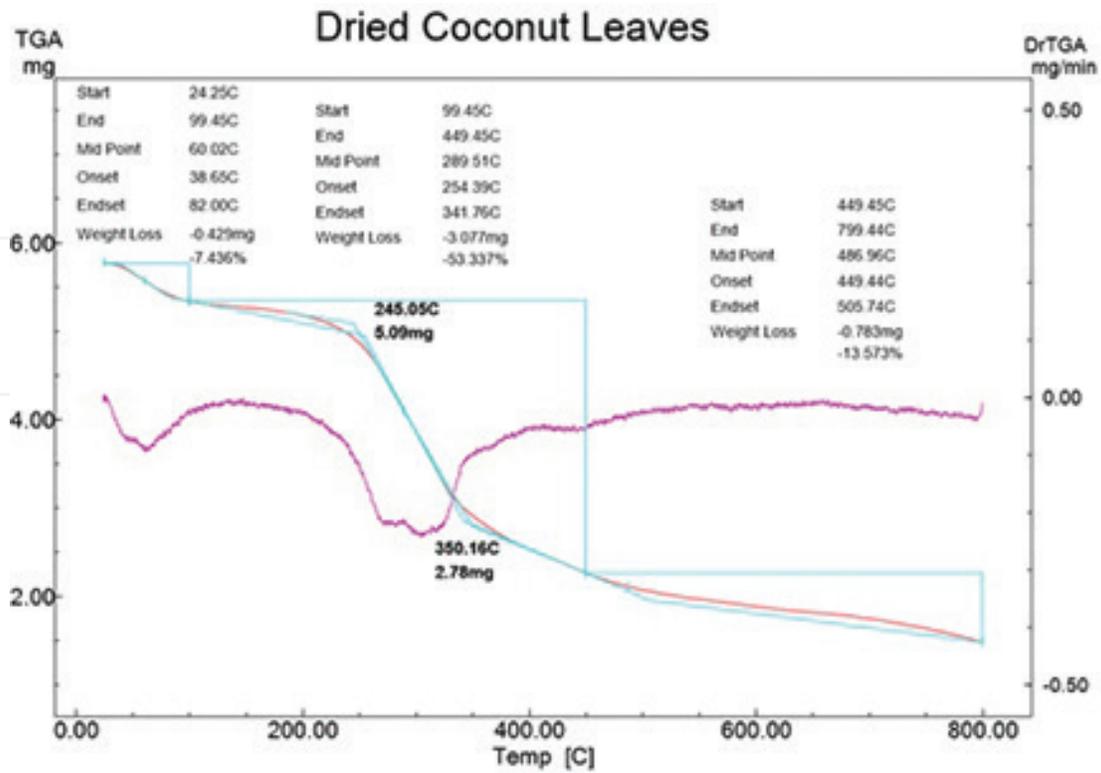


Figure 4. Thermogravimetric profile of dried coconut leaves.

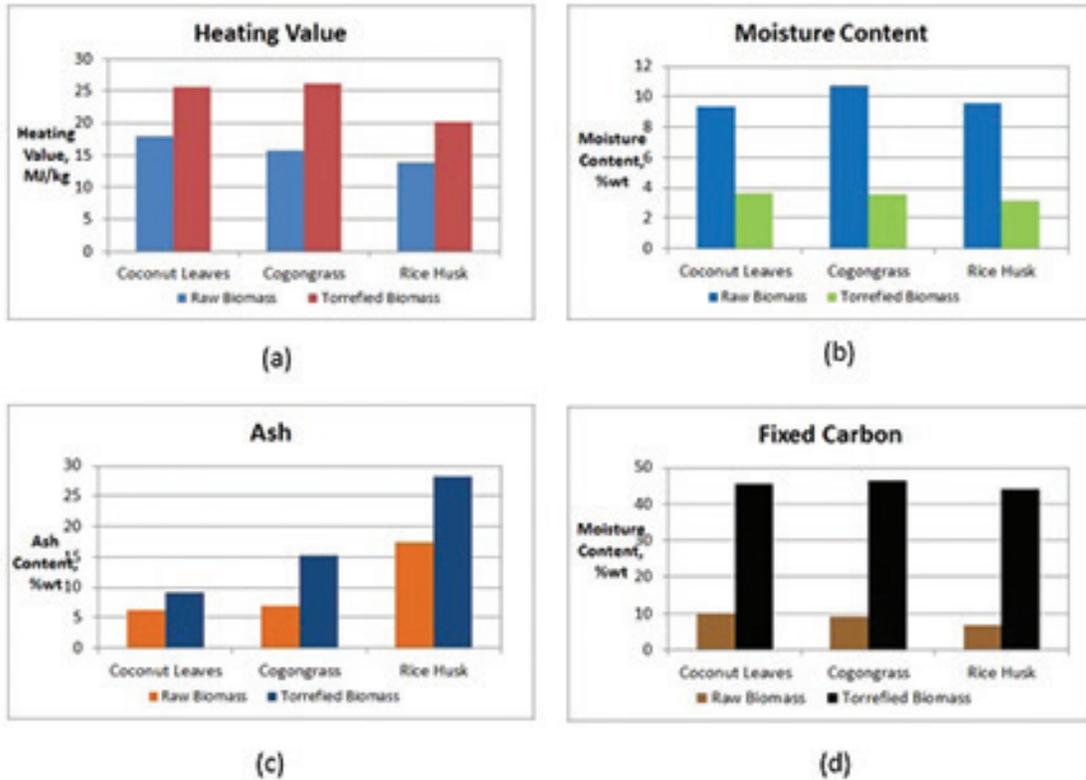


Figure 5. Fuel characteristics of the raw and torrefied biomass.

In some plant species, a significant fraction of the total biomass is not combustible and is recovered as ash from bioenergy processes. The amounts range from about 6% of dry weight in dried coconut leaves to about 9% in torrefied coconut leaves. Generally, the ash content of herbaceous biomass is higher than that of woody biomass. While ash weight content (in dry basis) values of less than 1% are expected for wood, different herbaceous biomass types have reported values ranging from less than 2% up to 8–10% or even up to 25% for rice husks. In waste fractions, the ash content may often be as high as 30–50% and is only scarcely less than 10% [30].

6.2. The torrefaction process design

6.2.1. Feedstock grinding

Standard-sized pellet mills generally require biomass that is ground to particles that are no more than 3 mm in size. Several types of equipment are available to carry out this task.

6.2.2. Moisture control

Maintaining an appropriate moisture level in your feedstock is vital for overall quality of the final pellets. For wood, the required moisture level of the feedstock is at or near 15%. Other types of biomass have other requirements—you may need to experiment a bit. Moisture can be removed from the feedstock by oven-drying or by blowing hot air over or through the particles. If the feedstock is too dry, moisture can be added by injecting steam or water into the feedstock [31].

6.2.3. Torrefaction

Torrefaction is usually performed in inert atmosphere at temperature below 300°C that aims to remove mostly the major hemicellulose contents from biomass structure [32, 33].

A typical torrefaction process is presumed to comprise drying of the biomass feedstock to have a biomass feed of constant moisture content to torrefaction, which also implies a more or less constant heat duty to be delivered to the torrefaction reactor. Furthermore, it is expected that the best destiny for the liberated torrefaction gas is to combust it to generate heat for the drying and torrefaction processes, which requires a combustible torrefaction gas [34].

6.2.4. Pulverizing and pelletizing

Torrefied biomass can be subjected to pulverizing and pelletizing to produce fuel pellets. A roller is used to compress the biomass against a heated metal plate called a “die.” The die includes several small holes drilled through it, which allow the biomass to be squeezed through under high temperature and pressure conditions. If the conditions are right, the biomass particles will fuse into a solid mass, thus turning into a pellet [35].

The torrefaction process is quite simple as **Figure 6** shows. Our pre-feasibility study for a commercial plant shows an investment of USD 1 million, whereas a Belgian company offers USD 25 million. We are designing small-scale units that can be operated by Local Government Units (LGUs) at subsidized cost.

In order to promote the wider use of biomass resources for energy generation, three A’s have to be satisfied: A—appropriate to varying local conditions, A—affordable to a wide sector of the population and A—available along with the necessary support services and program back-up.

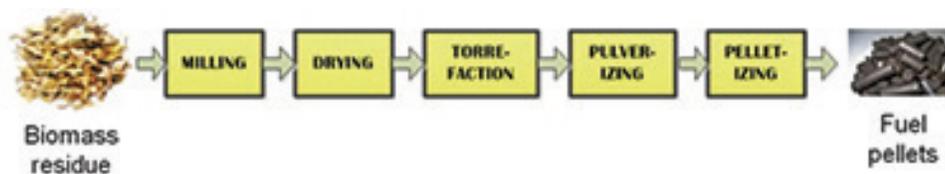


Figure 6. The complete torrefaction process.

Above measures will make biomass technologies as an attractive option to potential users [36].

7. Conclusion

Torrefaction can convert low-grade biomass to solid fuel with properties similar to subbituminous coal that can be used for industrial and domestic applications. Torrefaction results on coconut leaves showed that the moisture content was reduced by 67% compared to the raw material, and the heating values, fixed carbon, and ash content were increased from 20 to 26 MJ/kg, 44 to 46%, and 9 to 28%, respectively. These values approach that of typical subbituminous coal with calorific values ranging from about 19 to 26 MJ/kg. The proposed torrefaction process is cheaper, less complicated, and more convenient to handle compared to the pyrolysis or gasification. It is appropriate and suitable for application with biomass.

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