Journal of the Nigerian Association of Mathematical Physics
***Volume 54* (January *2020 Issue*), pp195 – 200**

COMPREHENSIVE STUDY OF BIOMASS TECHNOLOGY AND ITS APPLICATION: A REVIEW

Akpu N.I.[1], Nnanna L.A.[2] and M.O. Akpu[3]

[1&2]Department of Physics, Michael Okpara University of Agriculture, Umudike, PMB 7267 Umuahia, Abia State, Nigeria
[3]Department of Physics, Nasarawa State University Keffi, Nasarawa State, Nigeria

Abstract

The world's energy markets rely heavily on the fossil fuels coal, petroleum crude oil, and natural gas as sources of thermal energy; gaseous, liquid, and solid fuels; and chemicals. Since millions of years are required to form fossil fuels in the earth, their reserves are finite and subject to depletion as they are consumed. The only natural, renewable carbon resource known that is large enough to be used as a substitute for fossil fuels is biomass. This article gives an overview of the state-of-the-art of various biomass conversion technology currently deployed which can serve many different energy needs from large-scale industrial applications to small-scale, rural end uses and technologies that may play a key role in the future. These processes ranges from thermal, thermochemical, biochemical and finally chemical processes which were properly outlined and explained. Different types of solid, liquid or gaseous fuels exist in bioenergy. Such fuels can be utilized in transportation, engine and turbine electrical power generation. Chemical products can also be obtained from all organic matter produced. These aforementioned conversion technologies and processes can convert biomass resources into power, heat and fuels for potential use. Bio-refinery integrates biomass conversion processes and equipment to produce fuels, power and value added chemicals from biomass. The nature, advantages, environmental impact and challenges related to these technologies were also highlighted.

Keywords: Biomass conversion technology, Bioenergy, Bio-refinery,Environmental impacts of biomass.

1.0 Introduction

The world's energy markets rely heavily on the fossil fuels such as coal, petroleum crude oil, and natural gas as sources of thermal energy; gaseous, liquid, and solid fuels; and chemicals. Since millions of years are required to form fossil fuels in the earth, their reserves are finite and subject to depletion as they are consumed. The only natural, renewable carbon resource known that is large enough to be used as a substitute for fossil fuels is biomass [1, 2].

Biomass being a renewable source of energy is readily available and environmentally friendly. The amount of carbon, biomass can release to the environment during combustion is equivalent to the amount of carbon it absorbed during its life time through photosynthesis; also, the lower emission of the environmentally detrimental gasses such as sulphur dioxide (SO_2) and nitrogen oxide (NO_2) during combustion. Biomass plays a positive role in reducing the acid rain formation. It is a good renewable source of energy. The combustion of flexibility and efficiency to the development of technology for converting biomass to bio-product has attracted significant attention in the recent years [3].

Unlike fossil fuel deposits, biomass is renewable in the sense that only a short period of time is needed to replace what is used as an energy resource [1]. The capture of solar energy as fixed carbon in biomass via photosynthesis, during which carbon dioxide (CO_2) is converted to organic compounds, is the key initial step in the growth of virgin biomass and is depicted by the following equation:

$$CO_2 + H_2O + \text{Light} + \text{Chlorophyll} \rightarrow (CH_2O) + O_2 \qquad 1.1$$

Equation1.1 is the general photosynthesis equation where carbondioxide(CO_2), water (H_2O) and energy from the sun (light) reacts to produce carbohydrate and oxygen. Carbohydrate, represented by the building block (CH_2O), is the primary organic product. For each gram mole of carbon fixed, about 470 kJ (112 kcal) is absorbed.

Corresponding Author**:** Akpu N.I., Email: akpu.nwamaka@mouau.edu.ng, Tel: +2348037335729

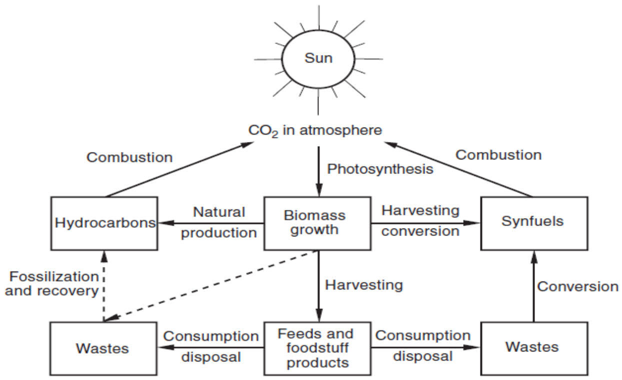

Figure 1: Main features of biomass energy technology [2].

1.2 Biomass Classification

According to [3] and [4], biomass which is defined as any organic matter that can be used as an energy source can be classified into four which are:

i. Agricultural and forestry residue: Silviculture crops
ii. Herbaceous crops: Weeds, Napier grass.
iii. Aquatic and marine biomass: Algae, water, hyacinth, aquatic weeds, plants see grass beds, kelp and coral reef etc.
iv. Waste: municipal solid waste, municipal sewage sludge, animal waste and industrial waste, etc.

2.0. Biomass Technologies and Conversion Processes

Biomass energy technologies capture the energy stored in biomass and make it available in useful forms. There are a number of technological options available to make use of a wide variety of biomass types as a renewable energy source. Conversion technologies may release the energy directly, in the form of heat or electricity, or may convert it into another form, such as liquid biofuel or combustible biogas. The choice of conversion process depends on the type, property and quality of biomass feedstock, the desired form of energy i.e. end use requirements, environmental standards, economic conditions and project specific factors [5]. The processes that convert biomass to energy can be separated into four basic categories.

2.1: Direct Combustion (thermal) Processes

Direct combustion is a conversion technique in which the biomass is burned in open air or in the presences of excess air. It is the most common use of biomass for residential space heating and cooking and for industrial process heating. In the residential sector, improved wood cooking and heating stoves can offer advantages in terms of reduced fuel requirements (thus, lower costs or less time spent collecting biomass) and improved emissions characteristics.

In this process the Feedstock's used are often residues such as wood, agricultural residues, straw, municipal solid waste (MSW) and wastes from the food industry and they are being converted into several forms of useful energy for commercial or industrial uses: hot air, hot water, steam and electricity [6]

Under Direct combustion Process we have the following

2.1.1 Cogeneration – This implies using a boiler to produce heat and electricity and it also improves overall system efficiency to as much as 85%. Two cogeneration arrangements are possible. Firstly steam can be used in an industrial process and then routed through a turbine to generate electricity. This arrangement is called a Bottoming Cycle. In the alternate arrangement, steam from the boiler passes first through a turbine to produce electric power and the steam exhaust from the turbine is then used for industrial processes or for space and water heating. This arrangement is called a Topping Cycle and is more common than the later.

2.1.2: Direct-firing gas turbine –This is another combustion technology for converting biomass to electricity.

Here fuel pretreatment reduces the biomass to a particle size of less than 2mm and a moisture content of less than 25%. Then the fuel is burned with compressed air. Cleanup of the combustion gas reduces particulate matter before the gas expands through the turbine stag. The turbine drives a generator to produce electricity [6].

2.1.3 Co-firing with coal - The practice which allowed biomass feedstocks an early and cheap entry point into the energy market is the practice of co-firing a fossil fuel (usually coal) with a biomass feedstock. It refers to the blending of biomass with coal in the furnace of a conventional coal-fired steam cycle electric power plant. This is currently one of the simplest ways of utilizing biomass to displace fossil fuels, requiring no new investment or specialized technology [4]. Co-firing is known to reduce carbon dioxide emissions, sulfur dioxide emissions, and potentially some emissions of nitrogen oxides as well. Co-firing has a number of advantages, especially where electricity production is an output especially where the conversion facility is situated near an agro-industrial or forestry product processing plant, large quantities of low-cost biomass residues are available [7].

2.2 Thermochemical Process

2.2.1 Pyrolysis

Pyrolysis is a thermochemical decomposition of organic material at elevated temperatures in the absence of oxygen. Pyrolysis typically occurs under pressure and at operating temperatures above 430^{o}C (800^{o}F).Ingeneral, pyrolysis of organic substances produces gas and liquid products and leaves a solid residue richer in carbon content. Liquid-phase products result from temperatures which are too low to crack all the long chain carbon molecules thus resulting in the production of tars, oils, methanol, acetone, etc. Once all the volatiles have been driven off, the residual biomass is in the form of char which is virtually pure carbon [8].

The pyrolysis process is used heavily in the chemical industry to produce charcoal, activated carbon, methanol and other chemicals from wood, to convert ethylene dichloride into vinyl chloride to make PVC, to produce coke from coal, to convert biomass into syngas, to turn waste into safely disposable substances, and for transforming medium-weight hydrocarbons from oil into lighter ones like gasoline [9].

Pyrolysis is the basis of several methods that are being developed for producing fuel from biomass, which may include either crops grown for the purpose or biological waste products from industries.

The advantage of pyrolysis is that it converts solid material into gases and vapours which are less costly to handle, transport and store. The gases will burn in boilers, gas turbines and reciprocating engines increasing fuel flexibility and security. Capturing and combusting the methane and carbon monoxide in syngas makes use of the energy in the gas and produces carbon dioxide which is a less potent greenhouse gas than methane and offsets fossil fuel energy production [10].

The disadvantageof pyrolysis is that it requires heat input to drive the chemical reactions that produce a syngas. Thus some fuel must be used to generate the syngas [2].

2.2.2 Torrefaction

Torrefaction is the thermal degradation of organic biomass in an inert or nitrogen atmosphere, one atmosphere pressure and temperature in the range of 200^oC – 300^oC for several hours depending on the biomass [11]. During the torrefaction process, the water contained in the biomass as well as superfluous volatiles are released, biopolymers partly decompose, giving off various type of volatiles. The final product is the remaining solid, dry, blackened material that is referred to as torrefied biomass or bio-coal [12]. Also Torrefied biomass can be produced from a wide variety of raw biomass feedstocks while yielding similar product properties.

Torrefied and densified biomass has several advantages which makes it a competitive option compared to conventional biomass (wood) pellets, such as [13];Higher energy density, More homogeneous composition, hydrophobic behavior, Elimination of biological activity, improved grindability etc. [14].

2.2.3 Carbonization

This is an age old pyrolytic process optimized for the production of charcoal. Traditional methods of charcoal production have centered on the use of earth mounds or covered pits into which the wood is piled. Control of the reaction conditions is often crude and relies heavily on experience (Sharma et al., 2014).

During carbonization most of the volatile components of the wood are eliminated; this process is also called ‘‘dry wood distillation’’. Carbon accumulates mainly due to a reduction in the levels of hydrogen and oxygen in the wood. The wood undergoes a number of physico-chemical changes as the temperature rises. Between 100^oC and 170^oC most of the water is evaporated; between 170^oC and 270^oC gases develop containing condensable vapors, CO and CO_2. These condensable vapors (long chain carbon molecules) form pyrolysis oil, which can either be used for the production of chemicals oras a fuel after cooling and scrubbing. Between 270^oC and 280^oC an exothermic reaction develops which can be detected by the spontaneous generation of heat [15].

There are three basic types of charcoal-making [2];(a) Internally heated (by controlled combustion of the raw material)(b) Externally heated (using fuel wood or fossil fuels) and (c) Hot circulating gas (retort or converter gas, used for the production of chemicals).

Internally heated charcoal kilns are the most common form of charcoal kiln. It is estimated that 10–20% of the wood (by weight) is sacrificed; a further 60% (by weight) is lost through the conversion to, and release of, gases to the atmosphere from these kilns. Externally heated reactors allow oxygen to be completely excluded, and thus provide better quality charcoal on a larger scale. They do, however, require the use of an external fuel source, which may be provided from the ‘‘producer gas’’ once pyrolysis is initiated. Recirculating heated gas systems offer the potential to generate large quantities of charcoal and associated by-products, but are presently limited by high investment costs for large-scale plants [4].

2.2.4 Gasification

Gasification is the partial oxidation of an organic feedstock to produce a syngas (a mixture of hydrogen, volatile short chain organic compounds, and carbon monoxide). The biomass is converted to simplified products, CO and H_2, in the optimized concentrations of oxygen and H_2O (steam reforming) at temperatures ≥800◦C which is completely distinct from gasification via anaerobic digestion. The final products are syngas (CO and H_2 mixture), CO_2, NO_x, SO_x, and ash/metal slag (quantity will depend upon the type of the waste: municipal, agricultural, or wood biomass). Syngas has multiple applications such as fuel cells, synthetic fuel, and chemical feedstock's [16]. Technically, gasification is an excellent method of extracting bioenergy free from N, P, S, Cl and metals contamination from diverse biomass types without further treatment/upgrading. Many biomass gasification processes are under development or at trial stage for biofuels and electricity generation, and waste disposal such as Enerkem, Thermoselect, GE Energy-Nexterra, Choren, among many others. However, positive electricity efficiency, biomass drying and grinding, oxygen input, reactor cleaning and maintenance, and economic feasibility are some major challenges for biomass gasification which are at research, pilot and demo scales [17].

2.2.5 Catalytic/Thermal Liquefaction

This technology has the potential to produce higher quality products of greater energy density. It is a low temperature, high pressure thermochemical conversion process carried out in the liquid phase. It requires either a catalyst or a high hydrogen partial pressure [2].

Thermal liquefaction can often be confused with pyrolysis in simplified comparisons. The two processes differ in operating parameters, requirement of catalyst, and final products. Liquefaction produces mainly liquid and some amounts of gaseous components at temperature and pressure ranges of 250–350◦C and 700– 3000 psi, respectively, in the presence of alkali metal salts as catalyst.

The liquefaction may also require supplemental CO and H_2 as reactants to facilitate the overall process. The mechanisms of liquefaction reactions lack sufficient description about role of catalysts [18]. The catalysts hydrolyse the cellulose, hemicelluloses, and lignin macromolecules into smaller micellar-like fragments, which are further degraded to smaller compounds via dehydration, dehydrogenation, deoxygenation, and decarboxylation reactions.

In comparison to torrefaction/carbonization, thermal liquefaction can provide liquid fuels in line with petroleum products along with several high value chemicals; however, recent trends in biomass thermochemical conversion, liquefaction, could not be successful at commercial scale [14]. The possible factors that limit the liquefaction commercialization could be the lower overall yield of oil (between 20–55% w/w) compared to contemporary options like pyrolysis, inferior oil quality (heavy tar like liquid), stricter operational parameters (higher reaction temperature and pressure), and requirements of catalysts and/or other reactants (CO, propanol, butanol, and glycerine).

2.3 Biochemical Processes

Biochemical conversion processes is a type of biomass conversion technology that usesbiocatalysts, such as enzymes, inaddition to heat and other chemicals, to convert the carbohydrate portionof the biomass (hemicellulose andcellulose) into an intermediate sugarstream. These sugars are intermediatebuilding blocks that can then befermented or chemically catalyzedinto a range of advanced biofueland value-added chemicals [19]. Theoverall process can be divided into;

2.3.1 Anaerobic Fermentation

Anaerobic digestion is the microbial digestion of feedstock releasing heat, methane, hydrogen sulphide, carbon dioxide and under specific conditions hydrogen gas. This process takes place over several days in any airtight container containing a mixture of bacteria normally present in animal waste [6]. After the process the remaining solid digestateis suitable for use as fertiliser and the gases released are collectively referred to as biogas. This gas can be used as a fuel in a CHP scheme once the gas has been cleaned to remove acidic compounds by condensation [2].

There are four key biological and chemical stages of anaerobic digestion;

1. **Hydrolysis**- In most cases biomass is made up of large organic polymers. In order for the bacteria in anaerobic digesters to access the energy potential of the material, these chains must first be broken down into their smaller constituent parts. These constituent parts or monomers such as sugars are readily available by other bacteria. The process of breaking these chains and dissolving the smaller molecules into solution is called **hydrolysis**. Therefore, hydrolysis of these high molecular weight polymeric components is the necessary first step in anaerobic digestion. Through hydrolysis the complex organic molecules are broken down into simple sugars, amino acids and fatty acids [4].

2. Acidogenesis - Acetate and hydrogen produced in the first stages can be used directly by methanogens. Other molecules such as volatile fatty acids (VFAs) with a chain length that is greater than acetate must first be catabolized into compounds that can be directly utilized by methanogens. The biological process of **acidogenes**is where there is further breakdown of the remaining components by acidogenic (fermentative) bacteria. Here, VFAs are created along with ammonia, carbon dioxide and hydrogen sulfide as well as other by-products.

3. Acetogenesis- This is the third stage of anaerobic digestion. Here, simple molecules created through the acidogenesis phase are further digested by acetogens to produce largely acetic acid as well as carbon dioxide and hydrogen.

4. Methanogenesis–This is the terminal stage of anaerobic digestion. Here, methanogens utilize the intermediate products of the preceding stages and convert them into methane, carbon dioxide and water. It is these components that make up the majority of the biogas emitted from the system. Methanogenesis is sensitive to both high and low pHs and occurs between pH 6.5 and 8. The remaining, non-digestible material which the microbes cannot feed upon, along with any dead bacterial remains constitutes the digestate.

The major advantage of anaerobic digestion is that it naturally occurs to organic material and would release methane, a potent greenhouse gas, into the atmosphere. Capturing and combusting the methane makes use of the energy in the gas and produces carbon dioxide which is a less potent greenhouse gas than methane and offsets fossil fuel energy production [2].

The disadvantages of anaerobic digestion are that the microbes required poses an environmental challenge to humans and livestock. The microbes are sensitive to changes in the feedstock, especially the presence of anti-microbial compounds, and changes in the reactor conditions: they require constant circulation of the reactor fluid, and a constant operating temperature and pH.

2.3.2 Methane Production in Landfills.

Methane is a powerful greenhouse gas, with substantial amounts being derived from unutilized methane production from landfill sites. Its recovery therefore, not only results in the stabilization of the landfill site, allowing faster reuse of the land, but also serves to lessen the impact of biospheric methane emissions on global warming. Anaerobic digestion in landfills is brought about by the microbial decomposition of the organic matter in refuse. The levels of organic matter produced per capita vary considerably from developed to developing countries [20].

Commercial production of land-gas can also aid with the leaching problems now increasingly associated with landfill sites. Local communities neighboring land fill sites are becoming more aware of the potential for heavy metals and nutrients to leach into aquifers. Landfill processing reduces the volume of sludge to be disposed of, and the nutrient content, thus facilitating proper disposal [2].

2.3.3 Ethanol Fermentation

Ethanol is mainly used as a substitute for imported oil in order to reduce their dependence on imported energy supplies. The substantial gains made in fermentation technologies now make the production of ethanol for use as a petroleum substitute and fuel enhancer, both economically competitive (given certain assumptions) and environmentally beneficial. The most commonly used feedstock in developing countries is sugarcane, due to its high productivity when supplied with sufficient water. Where water availability is limited, sweet sorghum or cassava may become the preferred feedstock. Other advantages of sugarcane feedstock includes the high residue energy potential and modern management practices which make sustainable and environmentally benign production possible whilst at the same time allowing continued production of sugar. Other feedstockinclude saccharide-rich sugarbeet, and carbohydrate rich potatoes, wheat and maize [2].

Ethanol fermentation, also referred to as alcoholic fermentation, is a biological process in which sugars such as glucose, fructose and sucrose are converted into cellular energy and thereby produce ethanol and carbon dioxide as metabolic waste products. Because yeasts perform this process in the absence of oxygen, ethanol fermentation is classified as anaerobic. Ethanol fermentation occurs in the production of alcoholic beverages and ethanol fuel, and in the rising of bread dough [21].

Recent advances in the use of cellulosic feedstock, may allow the competitive production of alcohol from woody agricultural residues and trees to become economically competitive in the medium term.

2.4 Chemical Process

2.4.1 Biodiesel Prodction

Another form of liquid fuel from biomass is ‘‘biodiesel’’, which is derived from the vegetable oils extracted by crushing oilseeds, although waste cooking oil or animal fats (tallow) can also be used. The oil is strained and usually ‘‘esterified’’, by combining the fatty acid molecules in the oil with methanol or ethanol. Vegetable oil esters have been shown to make good-quality clean-burning diesel fuel [6].

Biodiesel refers to a vegetable oil- or animal fat-based diesel fuel consisting of long-chain alkyl (methyl, propyl or ethyl) esters. Biodiesel is typically made by chemically reacting lipids (e.g., vegetable oil, animal fat (tallow)) with an alcohol. Biodiesel is meant to be used in standard diesel engines and is thus distinct from the vegetable and waste oils used to fuel converted diesel engines. Biodiesel can be used alone, or blended with petrodiesel [4].

3.0 BIOENERGY APPLICATIONS

Table 3.1: Summary of different biofuels and their application

Fuel state	Application
Biogas	Supplementing mains supply (grid-connected)
Biogas	Cooking and lighting (household-scale digesters), motive power for small industry and electric needs (with gas engine)
Liquid biofuel	Transport fuel and mechanical power, particularly for agriculture; heating and electricity generation; some rural cooking fuel
Solid biomass	Cooking and lighting (direct combustion), motive power for small industry and electric needs (with electric motor)

Table 3.1 summarizes the various biofuels we can get from biomass using different feedstocks and their application. From the table we observed that biomass is the only renewable energy source that has solid, liquid and gaseous fuel.

4.0 ENVIRONMENTAL IMPACTS

Several environmental impacts are directly related to biomass energy production and consumption.

The first is obviously the environmental benefit of displacing fossil fuel usage and a reduction in any adverse environmental impacts that are caused by fossil fuel consumption. In addition, the use of a fossil fuel and biomass together in certain applications, such as electric power generation with coal and wood or coal and RDF in dual-fuel combustion or cocombustion plants, can result in reduction of undesirable emissions. The substitution of fossil fuels and their derivatives by biomass and biofuels also helps to conserve depletable fossil fuels.

Another beneficial environmental impact results from the combined application of waste biomass disposal and energy recovery technologies. Examples are biogas recovery from the treatment of biosolids in municipal wastewater treatment plants by anaerobic digestion, LFG recovery from MSW landfills, which is equivalent to combining anaerobic digestion of waste biomass and LFG ‘‘mining,’’ and the conversion of MSW, refuse-derived fuel (RDF), and farm, forestry, and certain industrial wastes, such as black liquor generated by the paper industry, to produce heat, steam, or electric power. Resource conservation and environmental benefits certainly accrue from such applications.

Another environmental impact is more complex. It concerns the growth and harvesting of virgin biomass for use as dedicated energy crops. By definition, sustainable, biomass energy plantations are designed so that the biomass harvested for conversion to energy or fuels is replaced by new biomass growth. If more biomass is harvested than is grown, the system is obviously not capable of continued operation as an energy plantation [1].

Furthermore, the environmental impact of such systems can be negative because the amount of CO_2 removed from the atmosphere by photosynthesis of biomass is then less that that needed to balance the amount of biomass carbon removed from the plantation. In this case, virgin biomass is not renewable; its use as a fuel results in a net gain in atmospheric CO_2. Energy plantations must be designed and operated to avoid net CO_2 emissions to the atmosphere. A few biomass plantations are now operated strictly to offset the CO_2 emissions from fossil-fired power plants, particularly those operated on coal. Sometimes, the fossil-fired power plant and the biomass plantation are geographically far apart. It is important to emphasize that established IBPCSs that utilize dedicated energy crops will normally involve the harvesting of incrementally new virgin biomass production [1].

Finally, some of the environmental concerns relating to using biomass as a form of energy include the issue of land degradation and deforestation. On a long time scale, the sustainable yield depends on the balance between the rate of removal and replacement of the nutrient. The most elementary danger associated with biomass production is robbing the soil of its essential nutrient, a situation that may lead to the production of barren wastelands [6].

5.0 CONCLUSION

In conclusion, the only natural, renewable carbon resource known that is large enough to be used as a substitute for fossil fuels is biomass. This article gives an overview of the state-of-the-art of various biomass conversion technology currently deployed which can serve many different energy needs from large-scale industrial applications to small-scale, rural end uses and technologies that may play a key role in the future. These processes ranges from thermal, thermochemical, biochemical and finally chemical processes. Different types of solid, liquid or gaseous fuels exist in bioenergy. Such fuels can be utilized in transportation and also in engine and turbine electrical power generation. Chemical products can also be obtained from all organic matter produced. These aforementioned conversion technologies and processes can convert biomass resources into power, heat and fuels for potential use. Biorefinery integrates biomass conversion processes and equipment to produce fuels, power and value added chemicals from biomass. Its environmental impacts were also highlighted.

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