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Biomass Conversion Technologies for Bioenergy Generation: An Introduction

Abdurrahman Garba

Abstract

Over the last century, there has been increasing debate concerning the use of biomass for different purposes such as foods, feeds, energy fuels, heating, cooling and most importantly biorefinery feedstock. The biorefinery products were aimed to replace fossil fuels and chemicals as they are renewable form of energy. Biomass is a biodegradable product from agricultural wastes and residues, forestry and aquaculture. Biomass could be sourced from a variety of raw materials such as wood and wood processing by-products, manure, fractions of organic waste products and agricultural crops. As a form of renewable energy, they have the advantages of easy storage, transportation, flexible load utilization and versatile applications. The aim of this study is to provide an overview for thermochemical and biochemical biomass conversion technologies that were employed currently. Attention was also paid to manufacture of biofuels because of their potentials as key market for large-scale green sustainable biomass product.

Keywords: biomass, bioenergy, biochemicals, conversion routes, green chemistry

1. Introduction

Biomass can be regarded as any organic material that originated from plants or animals. Thus, the United Nations Framework Convention on Climate Change UNFCCC in 2005 [1], defined it as follows;

“A non-fossilized and biodegradable organic material originating from plants, animals and micro-organisms. This shall also include products, by-products, residues and waste from agriculture, forestry and related industries as well as the non-fossilized and biodegradable organic fractions of industrial and municipal wastes”.

The world's energy demand has been steadily increasing in the last several decades. This is due to rapid increase in industrialization, population and the quest for improvement of the living standards for societies. On the other hand, this has caused an irreversible damage to the environment which leads to global warming, and climate change. These issues have been the topic of discussion among scientist and policy makers at national and international levels on how to mitigate the problem. The modern society is emphasizing on shift from non-renewable to renewable energy (such as wind, solar, tide, geothermal and biomass) in their search for energy source. Before the discovery of fossil fuels such as petroleum products, coal, and natural

gas, biomass was the main source of energy for heating and cooking [2]. Biomass is the term used to describe all materials that contain carbon in an organic form. This organic form of carbon can be transformed into inorganic through photosynthesis by forming bonds with other elements such as hydrogen, and oxygen using solar energy. The demolishing of these bonds (molecules) through physical or biological means, causes a closure in the cycle and making CO_2 to be regenerated. During the regeneration process, energy is released which can be converted into other forms of energy. Therefore, as long as these equilibrium is maintained between use and regeneration, biomass is a renewable or inexhaustible source of energy [3]. Biomass is expected to be the leading form of energy with a significant global energy load of about 10–15%. However, biomass has a share of about 90% of total energy requirements for remote and rural areas of the developing countries. Therefore, it is likely to remain the future leading source of energy feedstock for the developing countries since about 90% of the world population is expected to live in the developing world by 2050 [4–6].

Biomass accumulates chemical energy in form of carbohydrates through combination of solar power and carbon dioxide during the process of photosynthesis. This has made it to be a potential energy source since the carbon dioxide captured during photosynthesis could be released when it burns. It is cheap and available in all forms such as forest and agricultural residues, wood, by-products of biological materials, organic components of municipal and sludge wastes, etc. There are several ways to convert biomass into useful products which largely depends on biomass characteristics and the end product [7]. The technologies applied in the conversion of biomass are mainly categorized under thermochemical or biological methods.

2. Types of biomass conversion technologies

Biomass can be converted into several useful products for energy generation and chemicals. There are some factors that influence the choice of a conversion technology to be applied on the biomass. These factors include quality and quantity of the biomass feedstock, availability, choice of end-products, process economics and environmental issues (**Figure 1**) [9].

2.1 Thermochemical methods

The major options within thermochemical biomass conversion processes include combustion, gasification, pyrolysis, and liquefaction (**Figure 2**). The most practiced thermochemical conversion of biomass industrially is combustion process, which is used for heat and electricity generation. Most of biomass thermochemical conversions were carried out with or without the use of catalysts, though the use of catalyst has distinct effects on the end-products [10].

2.1.1 Gasification

The process of biomass gasification was discovered independently in France and England by the year 1798. The technology did not come into its limelight until 60 years later. The gasification process continued flourishing until 30 years later when natural gas from oil fields was discovered. Until 1970, the use of natural gas for cooking and lighting was substituted with liquid fuels due to discovery of oil. Generally, biomass gasification is an endothermic thermochemical conversion of solid biomass fuel using gasifying agents such as air, steam or CO_2 to form a mixture of combustible gases which may include H_2 , CH_4 , CO and CO_2 . The process is carried out at temperatures between 800 and 1300°C. Nowadays, flexibility of the

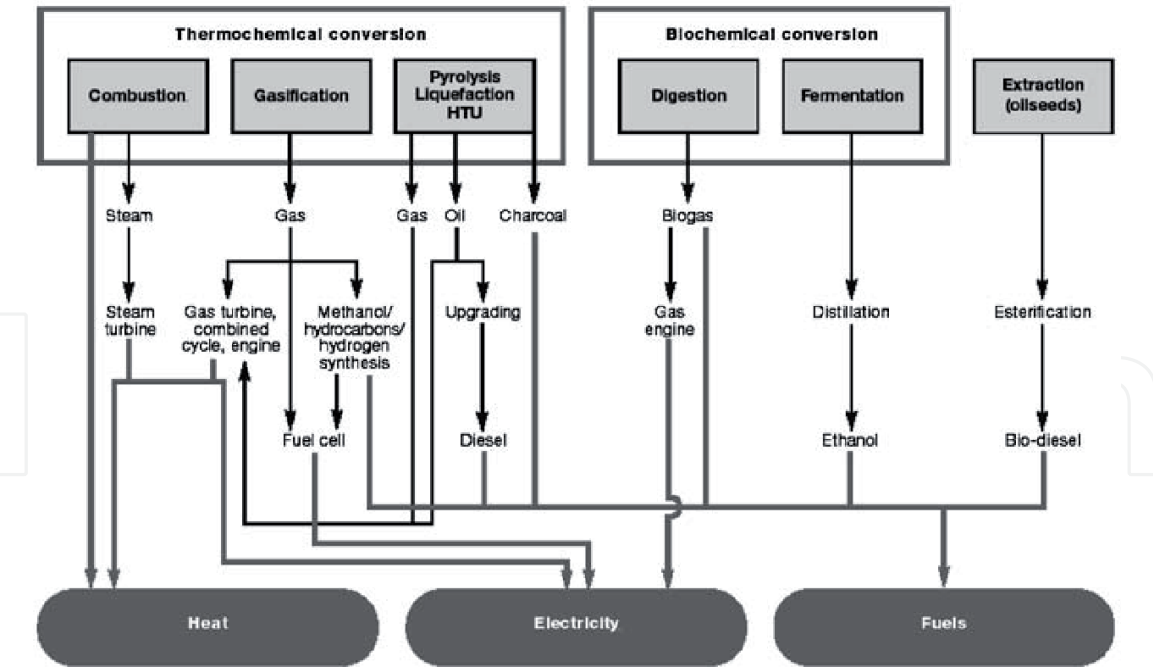


Figure 1.
Main biomass conversion routes [8].

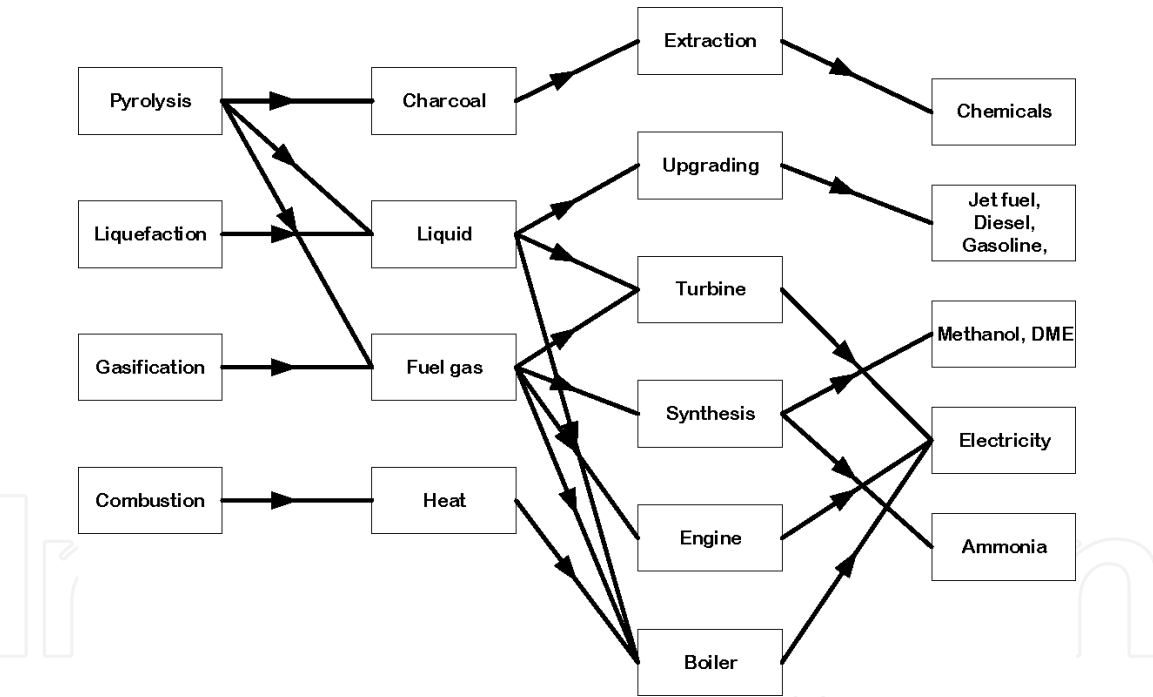


Figure 2.
Thermochemical conversion processes and end products [10].

gasification technology coupled with the different uses of the produced syngas, allows for the integration of biomass gasification with many industrial processes and as well with power generation systems [7].

Biomass feedstock characteristics such as particle size, moisture content, shape, heating value, carbon content and ash content significantly affect the gasifier performance. However, knowledge on feedstock parameters such as volatility, elemental analysis, heat content and biomass potential for fouling or slagging is essential for evaluation of gasification process [11]. Therefore, feedstock with low volatile contents are preferred for partial oxidation gasification, while those with high volatile content are more suitable for indirect gasification process [12].

Feedstocks for biomass gasification exists in different forms with each type having peculiar issues. Therefore, it is vital to predict suitable type of biomass for a specific gasifier type under defined conditions. Although, characteristics within specific biomass feedstock species is identical, the shape and size of the feedstock particles are useful in determining the difficulties that may arise during movement, delivery and as well as the feedstock behavior in the gasifier. The size and size distribution of the feedstock affect the gasification zone thickness, pressure drop in the bed and the maximum hearth load. To overcome some of this problems, biomass feedstock of uniform size were utilized [7].

Gasifier operation depends on moisture content of the biomass feed used. The use of feedstock with high moisture content reduces biomass conversion efficiency and as well the production rate. This is because the process discharges more fuel or heat in order to vapourize the excess moisture to the temperature of the syngas [13]. During the pyrolysis/gasification process, water need about 2.3 MJ/kg to vapourize and as well 1.5 MJ/kg to raise it to 700°C. Also, high moisture content in a biomass reduces the achieved temperature in the oxidation zone which results in incomplete cracking of the products released in the pyrolysis zone. Consequently, high moisture content in the biomass feedstock affect the syngas composition or quality due to production of CO₂ from reaction between the moisture. Furthermore, using feedstock that has high moisture content results in the production of syngas with high moisture, which subsequently course additional stress on downstream cooling and filtering equipment [14].

2.1.1.1 Hydrothermal gasification

Hydrothermal gasification is a biomass treatment that involves the use of water at high temperatures and pressures. Products formed during this process is as a result of different reactions that takes place in the biomass which mainly depends on factors like temperature, pressure, and time of treatment. To understand the process, behavior of water at high temperature and pressure must be known. **Figure 3** indicated the phase diagram of water, where at 273.15 K and atmospheric pressure (0.101325 MPa), ice melts to liquid water, while at 373.15 K liquid water boils and vapourized to steam. However, boiling point of water is affected by pressure and this means at high pressure the boiling point decreases, while at low pressure it increases. Likewise, pressure has

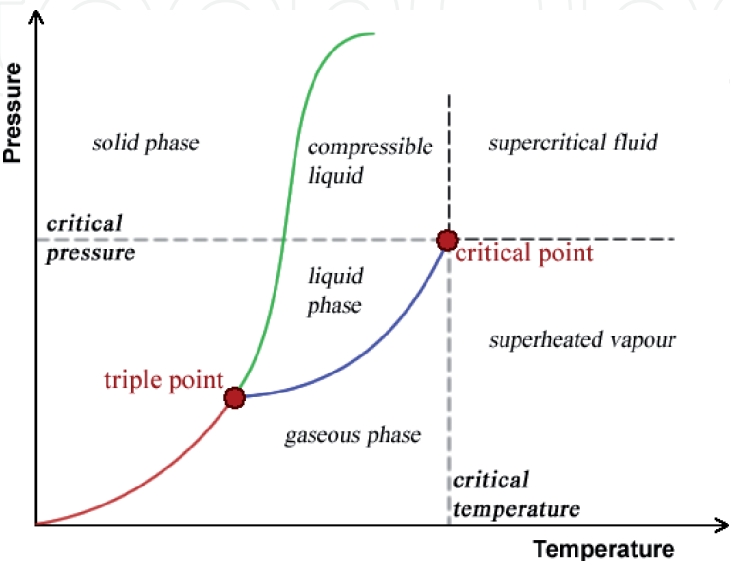


Figure 3.
Phase diagram of water [9].

effect on volume of water when it changes to steam. The volume of water increases greatly when it changes to steam. This change in volume is as high as 1600 times under atmospheric pressure.

At increased pressure, the volume of liquid water is not affected when compared to steam volume. Therefore, under increased pressure, the increase in volume associated with the phase change becomes smaller (**Figure 4**). The volumes for both water and steam were found to be equal at 22.1 MPa at the phase change. Also, when the pressure is higher than this value, no noticeable phase change is seen. At this point, the pressure is called the critical pressure of water, while the temperature is called critical temperature of water which corresponds to 647 K. This point on the phase diagram, is called the critical point. If the temperature and pressure are above these critical values, the water is called supercritical water, while when the values are below the critical values, the water is called subcritical [9].

Hydrothermal treatment of biomass can be carried out in either supercritical or subcritical water. That is when the temperature and pressure of the water is high. The process employs low temperatures ranging between 150 and 250°C. Under these conditions, the polymeric components of the biomass such as hemicellulose and lignin are dissolved together with small fraction of cellulose [15]. This process is mainly physical and requires harsh reaction conditions since the decomposition of the polymeric substances is limited. The process is often employed for saccharification of cellulose (**Figure 5**) or for an increased biomethanation of lignocellulosic biomass [16–18].

2.1.2 Pyrolysis

The term pyrolysis is defined as the thermal depolymerization of organic matter in the presence of nitrogen or absence of oxygen. Pyrolysis is an exothermic reaction with heat requirements that ranges between 207 and 434 kJ/kg of which many wood based and agricultural biomass were heated in an inert atmosphere to produce vapours and a carbon rich residue. The vapours composed of fragments from cellulose, hemicellulose and lignin polymers. These vapours can be condensed into free flowing organic liquid known as the bio-oil. On the other hand, the remaining carbon residues is left as bio-char (**Figure 6**) [20].

The polymeric substances distribution in bio-oil largely depends on the lignocellulosic contents of the biomass feed [21]. Many researchers investigated the individual pyrolysis characteristics of cellulose, hemicellulose and as well lignin. Hemicellulose was observed to decomposes at 220–315°C, cellulose decomposes between the range of 314–400°C, while lignin decomposition takes place from 160 to 900°C and it

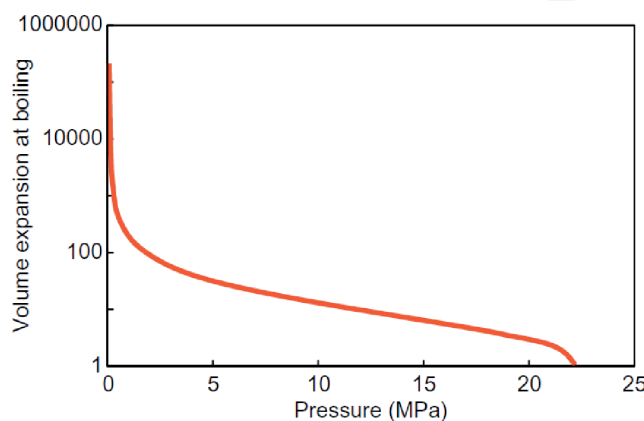


Figure 4.
 Pressure effect on volume change when water changes into steam [9].

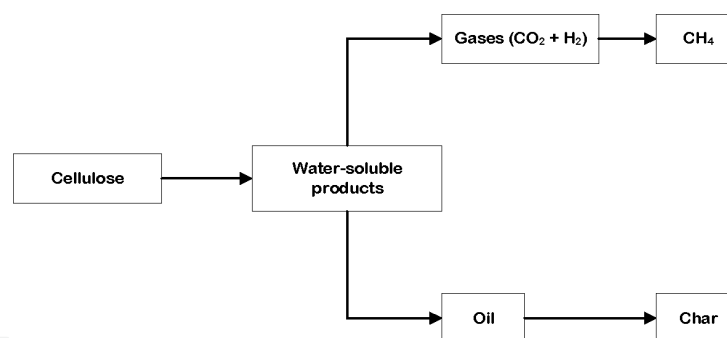


Figure 5.
Reaction network for hydrothermal gasification of cellulose [9].

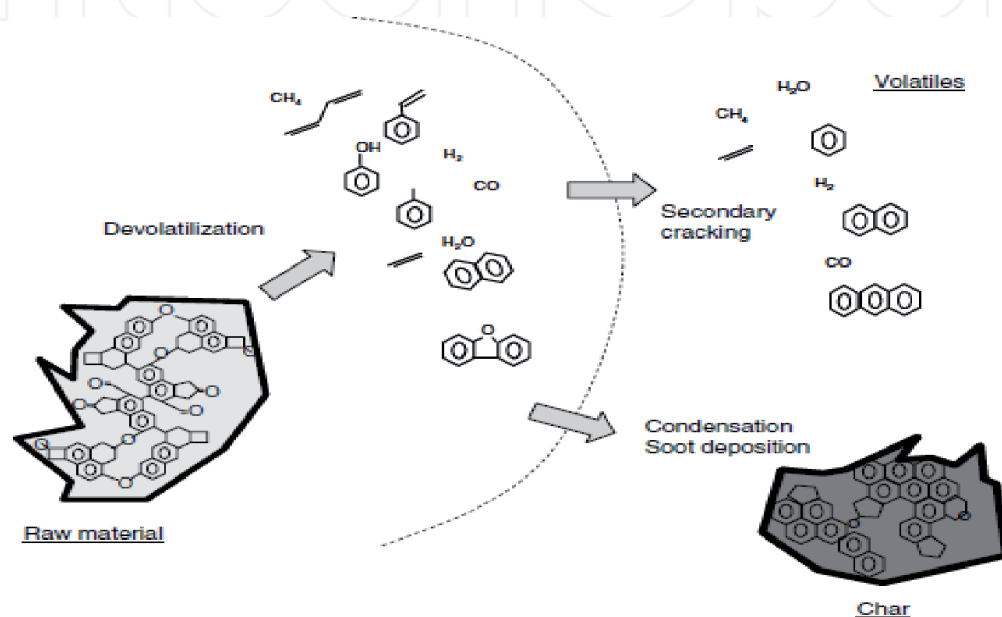


Figure 6.
Carbonization reaction scheme of a carbonaceous material [19].

generates a solid residue with highest percentage of about 40% [22]. From energy view point, cellulose pyrolysis was observed to be an endothermic reaction, while the reactions of hemicellulose and lignin is an exothermic. The gaseous products obtained from pyrolysis of these three components were similar and mainly comprises of CO_2 , CO , CH_4 and other organic gases. Micro-GC was employed to analyzed the releasing behaviour of the H_2 and total gases released when the three gases were pyrolyzed in a packed bed. Hemicellulose was observed to have higher yield for CO_2 , cellulose gives higher yield for CO with high presence of aromatic ring and methoxyl, while the lignin cracking and deformation yields higher H_2 and CH_4 . Cellulose pyrolysis involves the cleavage of glycosidic groups via dehydration which is followed by the breakdown of anhydroglucose units. The dehydration and breakdown of sugar molecules at lower temperatures, results in the formation of char. Shafizadeh and Fu [23] reported char yield of 34.2% for the pyrolysis of pure cellulose in the absence of air and at 300°C . At high temperatures, there is enough energy to initiate the rapid cleavage of glycosidic bonds and evaporation of gaseous products was favoured. However, the distribution of cellulose, hemicellulose and lignin in a bio-oil is predominantly determined by the interactions between these components rather than just their quantities. Rowell [24] suggested that hemicellulose and cellulose were bonded through hydrogen bond, while hemicellulose and lignin were covalently bonded via ester bonds. The bonds that exist between these polymeric substances influence the pyrolytic behaviour of the biomass which may bring about a difference in products distribution when

compared to a sample prepared synthetically by physical mixing. Couhert *et al.* [25] pyrolyzed two mixtures at 950°C containing the three components. One of the mixtures was prepared by simple mixing, while the other was prepared by intimate mixing. He discovered that, the yield for CO₂ increases with an increase in intimacy of the mixture. Hence, the effect of components interaction may differ in a physical mixture in comparison with the actual biomass sample, because the structure of the biomass can affect pyrolysis outcome which alter selectivity for certain products [26].

The necessary conditions for pyrolysis are temperature, pressure, heating rate, residence time, environment, catalyst, etc. This conditions greatly determines the nature of the products formed after pyrolysis [27]. Therefore, the pyrolysis conditions can be adjusted to obtain a desired product. It is well known from literatures that high temperature and short residence time favours formation of condensable fractions, high temperatures and longer residence time favours non-condensable gaseous products, and as well solids fractions are only favoured at low temperatures [28]. Depending on the pyrolysis conditions, the process can be classified as follows;

2.1.2.1 Fast pyrolysis

Recently, fast pyrolysis which is an advanced technology is gaining attention because of an increasing need for the production of fuel oil from biomass. As a continuous process, fast pyrolysis is aimed to prevent further cracking of the pyrolytic fractions to non-condensable compounds. During the process, the parameters that give high oil yield were carefully controlled in which the primary parameter is high rates of heat transfer. This parameter could be achieved by grinding the biomass feed finely. The finely ground biomass feed is heated rapidly at high temperatures between 450–600°C for a very short residence time of typically less than 2 seconds. The liquid yield for wood fast pyrolysis was reported to be as high as 75% [29, 30]. Since the process takes place in a very short period, not only chemical kinetics, but rate of heat and mass transfer, and as well transition phenomena plays an important role in determining the chemistry of the end products. Tailored products could be obtained by setting the necessary parameters at optimum [29].

2.1.2.2 Intermediate pyrolysis

In comparison with fast pyrolysis, intermediate pyrolysis is operated at optimum temperature range of 300–500°C. The liquid products obtained during the process is less viscous and contains low tar. However, the chemical reactions taking place during intermediate pyrolysis are more controlled and thus the process offers a wide range of parameter variations for process optimization. Although low yield for liquids of up to 55% were obtained during this operation, large sizes for biomass feed are acceptable that may be coarse, chopped, shredded or ground [31].

2.1.2.3 Slow pyrolysis

Slow pyrolysis is the carbonization of a biomass feed without condensing the pyrolysis products. The process is carried out in batches at low temperatures, slow heating rate and for a long residence time. Though, most of the literatures present about the process were based on its use to produce solid fuels such as charcoal and bio-char, but it can also be used to produce liquid fuels and bio-gas [32]. Temperatures as low as 0.1–2°C were reported by literatures. Slow pyrolysis is the oldest technique used for biomass conversion when the desired end product is charcoal or biochar. The vapours produced during the process were not condensed usually, but they could be used in the process to directly or indirectly provide heating. Moisture of about

15–20% were reported and it affects the properties of the solid fuels produced during the process [20]. The biomass feed sizes can vary from ground to a whole log.

2.1.3 Torrefaction

Torrefaction is a slow and mild pyrolysis process that is usually carried out at low temperatures between 225°C–300°C. The process is aimed at increasing the biomass energy density and as well its fuel properties [33]. This is achieved by removal of biomass moisture content and other superfluous volatiles. During the process, the biopolymeric substances such as cellulose, hemicellulose and lignin were partly decomposed to release organic volatiles. The product obtained at the end of the process is a dry and black residual solid regarded as torrefied biomass. The torrefied biomass is hydrophobic and soft which can easily be crush, grind or pulverized [20, 33].

2.1.4 Combustion

The process of combustion is a widely applied biomass conversion technology that was functional to a sizeable portion of human race since the advent of human civilization. It is widely applied even today for burning of wood and agricultural residues to make pot fires and stoves in order to provide heat and light energy for cooking and heating. Combustion process is frequently used for the conversion of lignin-rich biomass. The process could be applied in two broad ways, that is either by direct conversion of the whole biomass feedstock or by biochemical conversion in which some portions of the biomass remained. Compared with the other biomass conversion technologies, the process is largely non-selective in terms of the biomass feedstock. During the process, biomass feedstock is converted to CO₂ and water including smaller amount of other species which depends on the composition of the biomass and the process parameters. However, combustion of biomass largely depends on energy content of the feedstock. The amount of heat energy released during the process depends on feedstock energy content and as well as the conversion efficiency of the reaction. The fact that biomass feedstock composition plays a vital role in the combustion process was well established by many researchers worldwide in various reports [34–36]. The major share of energy in the biomass is formed by the assembly of organic matter during photosynthesis and respiration in plants. However, the inorganic fractions in the biomass are important in design and operation of the combustion system, especially when using the fluidized bed reactor. The amount of volatile matter in biomass feedstock is higher when compared with its fossil counterpart in which it is around 70–80%. The presence of this high volatile matter, greatly influence the thermal decomposition of the biomass feedstock and as well as the combustion performance of the solid fuels. This is because, large portion of the biomass feedstock has to be vapourized before the homogeneous combustion reaction takes place and the remaining char will then undergo heterogeneous combustion reaction.

The main elements that constitutes the biomass feedstock are C, H, and O, while herbaceous feedstock such as agricultural waste and grasses contain higher amounts of ash forming minerals [37, 38]. Biomass is more oxygenated compared to the conventional fossil fuel. This is due to the biomass carbohydrate structure and its dry mass usually contains about 30–40% oxygen [37]. During the combustion process, part of the oxygen required is supplied by the organically bonded oxygen from the biomass, while the rest is supplied through air injection into the system. The primary constituent of a biomass is carbon which made up about 30–60% by weight of dry matter depending on its ash content. The carbon present in biomass

feedstock is in partly oxidized form and this justifies the low gross calorific value of biomass feedstock when compared to coal. Of the biomass organic components, hydrogen is the third most important constituent that made up of about 5–6% of the dry matter. Other elements that are found in smaller quantities in the biomass (less than 1%) are Nitrogen, Sulfur and Chlorine, with the exception of agricultural residues where their figures are sometimes above 1% [39, 40]. The presence of high amount of such inorganic elements in a biomass feedstock leads to serious operational problems such as agglomeration, deposition, fouling, sintering and corrosion or erosion. Combustion process, unlike biochemical and other thermochemical conversion technologies, is largely nonselective in terms of biomass feedstock selection and the process aims to reduce the entire fuel to simple products. However, this shows that the complex nature of the biomass has substantial influence on its combustion performance. Inorganic elements such as Si, K, S, Cl, P, Ca, Mg and Fe are associated with reactions that leads to ash fouling and slagging (**Figure 7**) [36].

2.2 Biochemical methods

Biochemical biomass conversion technologies refer to conversion of biomass through biological pre-treatments. These pre-treatments were aimed to turn the biomass into a number of products and intermediates through selection of different microorganisms or enzymes. The process provides a platform to obtain fuels and chemicals such as biogas, hydrogen, ethanol, butanol, acetone and a wide range of organic acids [42]. However, this process was aimed at producing products that could replace petroleum-based products and as well as those obtained from the grains. Biomass biochemical conversion technologies are clean, pure, and efficient when compared with the other conversion technologies [43].

2.2.1 Digestion

Anaerobic digestion (AD) is one of the most sustainable and cost-effective technology for lignocellulosic and other form of waste treatment for energy recovery in form of biofuels. This process does not only minimize the amount of waste, but also transforms such waste into bioenergy. Also, the digestates produced during the process are rich in nutrients, which can serve as fertilizer for agricultural purposes [44].

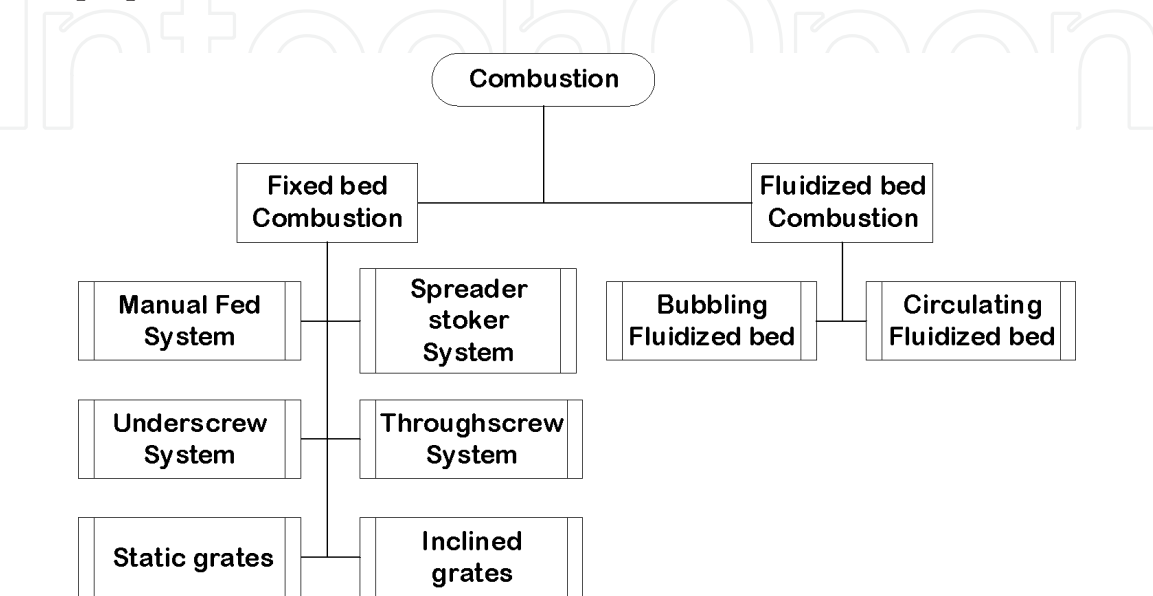


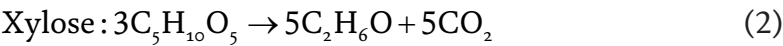
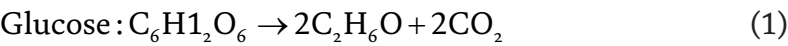
Figure 7.
Various reactors for combustion process [41].

The digestion of lignocellulosic biomass anaerobically produces energy rich methane (CH₄). The CH₄ yield per unit area is usually employed for the determination of energy output of an individual feedstock which significantly varies between species and as well with maturity, location and inputs (such as fertilizer, water etc.) within the same variety (Yang et al., 2013). The Biochemical methane potential (BMP) test is commonly used to evaluate the anaerobic digestibility of a biomass substrate. The biomass yield and CH₄ production potentials of some selected feedstocks were presented in **Table 1** [45].

Anaerobic digestion is a process used to produce biogas through biological treatment of biomass. It is performed at temperature ranges between 30 and 35°C, or 50 and 55°C using two stages. The first stage is the breaking down of the complex organics in the biomass by acid-forming bacteria into simpler compounds such as acetic and propionic acids along with volatiles. The second stage is conversion of such acids into CO₂ and CH₄ commonly called biogas through the use of methane producing bacteria. Usually, both stages of biogas production are performed in a single tank. The produced biogas contains about 60% CH₄, 35% CO₂, and a mixture of other gases such as H₂, NH₃, CO, and H₂S which account for about 5%. The biogas has a heating value of about 22,350 KJ/m³ for a mixture that contains a ratio (CH₄:CO₂:inerts) of 60: 35: 5 (**Figure 8**) [46].

2.2.2 Fermentation

Fermentation is a biological process that is commonly facilitated by secretion of enzymes sourced from microorganisms which converts simple sugars to low molecular weight structures such as alcohols and acids. The fermentation of two most common sugars follow the two reactions below:



During fermentation, biomass could be converted into alcohols through biochemical pathways. These pathways involved several schemes in which hydrolysis

Biomass	Biomass yield (ton wet weight/ha)	CH ₄ potential (Nm ³ CH ₄ /tonVS)
Sugar beet	40–70	387–408
Fodder beet	80–120	398–424
Maize	40–60	291–338
Wheat	30–50	351–378
Triticale	28–33	319–335
Sorghum	40–80	286–319
Grass	22–31	286–324
Red clover	17–25	297–347
Sunflower	31–42	231–297
Wheat grain	06–10	371–398

Table 1.
The biomass yield and methane potential of some selected lignocellulosic biomass [45].

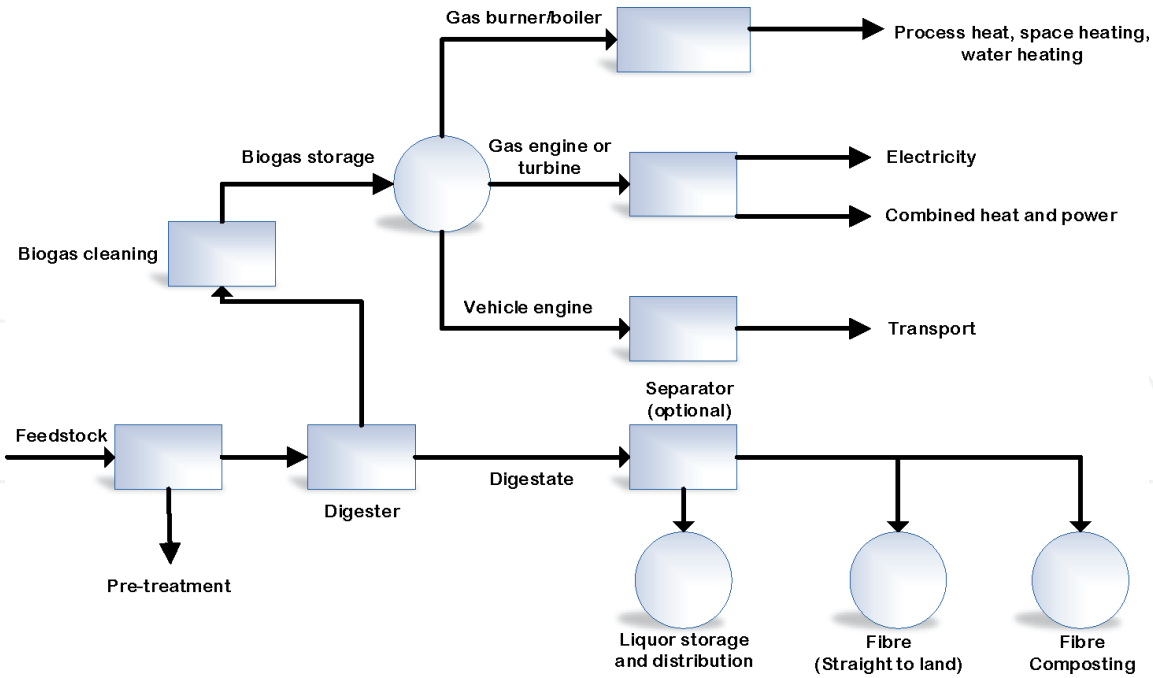


Figure 8.
Anaerobic digestion process [46].

Process	Substrate	Pre-treatment	Ethanol Conc., g/L	Ethanol Pro., g/L/h
SHF	<i>Parthenium hysterophorus</i> L.	Acids/alkali	13.6	—
	<i>Arundo donax</i>	Steam explosion	20.6	0.21
	Wheat straw	Steam explosion	—	0.313
SSF	<i>Miscanthus sacchariflorus</i>	CHEMET with NaOH	69.2	1.24
	Reed	phosphoric acid-acetone	55.5	0.57
	Reed	Liquid hot water	39.4	0.66
	<i>Liriodendron tulipifera</i>	Acid-free organosolv	29.9	0.42
	Corn stover	Steam explosion	25.7	0.36
SSCF	<i>Miscanthus giganteus</i>	Dilute oxalic acid	12.1	0.13
	Industrial hemp	Steam explosion	21.3	0.30
	Wood chips	Steam explosion	32.9	0.34
	Wheat straw	Steam explosion	—	0.7
CBP	Corn stover	Acid hydrolysis	—	0.27

SHF = *Separate hydrolysis and fermentation.*
SSF = *Simultaneous saccharification and fermentation.*
SSCF = *Simultaneous saccharification and co-fermentation.*
CBP = *Consolidated Bioprocessing.*

Table 2.
Processes in bio-ethanol production [47].

and fermentation process are carried out either concurrently in the same reactor or separately [47]. The different processes involved for alcohols production are presented in **Table 2**.

Conversion of biomass feedstocks through fermentation process is a vital issue because it allows for the production of wide range of substances under mild

conditions. The extent of fermentation on organic substances largely depends on composition and structure of the biomass feedstock. Only feedstocks that are not competing with the food items in terms of demand should be selected for biofuel production. Consequently, residues and waste materials from agriculture and forestry were considered as the most interesting sources of biomass.

High hydrolysis ratio is also an important requirement for the effective utilization of monosugars present in lignocellulosic structures. From biochemical perspective, organic substances present in the hydrolyzed solution can be categorized into several groups such as simple and complex carbohydrates, lipids, proteins, and heteropolymers. The potentials for biogas and biohydrogen generation from lignocellulosic biomass is huge due to utilization of different microorganisms in the conversion of cellulose and hemicellulosic fractions of the agricultural and forestry residues [47]. However, a major setback is usually encountered during biofuels production which is the conversion ratio of the polymeric substances into fermentable sugars like hexoses and pentoses due to production of inhibitors along with the desired products. To minimize such inhibitors and maximize hexoses and pentoses production, microbial metabolism in the degradation and saccharification of the biomass cell wall were considered [48, 49].

3. Conclusion

Currently, the use of lignocellulosic biomass as raw material for the generation of bioenergy has received a considerable attention for the development of sustainable ways for production of energy. Most of the researches conducted for biomass conversion technologies heads towards discovery of advanced ways to produce energy fuels so as to tackle its shortage that the world is facing. Also, the studies are aimed towards reduction of greenhouse gases and other harmful effects posed by fossil fuels to the environment.

From above, it can be concluded that biomass is a green source of energy in recent times. The study also indicated that thermochemical and biochemical technologies for the conversion of biomass into different energy products was started several decades ago, but it slowed down due to the discovery of fossil fuels. The biomass conversion technologies gained momentum recently due the fact that it is clean, sustainable and renewable source of energy.

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