Chapter

Combustion Characteristics and Behaviour of Agricultural Biomass: A Short Review

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Abstract

Biomass energy is one of the alternative sources of energy, which is particularly accessible in huge quantity worldwide in rural areas. Globally, solid biomass waste is the fourth as an energy resource after coil, oil and gas, which was providing approximately 14% of the world's energy needs. The potential of biomass materials depends on feedstock quantities and their composition. The use of biomass materials as energy source provides extensive benefits as far as the environment is concerned. The agricultural biomass materials absorb carbon dioxide (CO_2) during growth and emit it during combustion. Utilization of these types of wastes in various applications is in the form of a renewable and CO_2-neutral fuel. The physicochemical and structural analyses of agricultural biomass differ significantly with the feedstock types. This review study provides an alternative approach and better understanding to utilize huge amount of energy stored in biomass as the substitute of fossil fuels and also it should play an important role in sustainable energy systems as a component of a renewable energy mix.

Keywords: biomass, combustion characteristics, physicochemical properties, renewable energy, bio-energy

1. Introduction

Energy is most imperative need of human life. Energy consumption pattern indicates the social and economic development of any country [1]. Primary energy sources (natural gas, oil, coal) are considered as the main energy sources in the world [2]. **Table 1** shows the world's primary energy demand that is projected until 2035. As clearly can be seen, as the total worldwide demands for energy keep increasing year-by-year, biomass and other renewables are expected to gain significant contributions in meeting these demands. The world's depleting fossil fuels and increasing Green House Gas (GHG) emissions have given rise to much research into renewable and cleaner energy. In 2010, 76% of total GHG emissions, CO_2 remain the major anthropogenic GHG with the increasing fossil CO_2 emissions more than trebling from 420 $GtCO_2$ in 1970–1300 $GtCO_2$ in 2010 [3]. Since 2000, emissions of anthropogenic CO_2 have risen by more than 3% per year with the net addition likely to rise to 8–12 GtC by 2020 and as much as 6–23 GtC by 2050 [4, 5].

The concern over global warming and climate changes has stimulated a search for alternatives of energy that are renewable and environment friendly. There are various forms of energy sources that are abundantly available which includes nuclear, wind, solar, biomass, waste materials, geothermal, tidal, hydro, etc. The exploitation of these energy sources are growing in different parts of the world and its potential depends on various aspects such as, energy policy target, renewable energy market, technology development and topographical regions [6, 7].

Renewable energy resources that use domestic resources have the potential to provide energy services with zero emissions of both air pollutants and greenhouse gases [8]. Among the various renewable energy sources, biomass has the potential to be used as alternative source of energy with CO_2 neutral [9]. Apart from this, less content of N and S as compared to the fossil fuel makes it environment friendly and does not promote acid rain or greenhouse gas emission [10]. Biomass is a potentially important source of renewable energy in agricultural countries because of abundant supply and its low prices (**Table 1**).

1.1 Bio-waste sources

Bio-waste materials includes woody crops and wastes, agricultural wastes, bagasse, waste paper, sawdust, municipal solid waste, waste from food processing, and animal or cattle wastes. These wastes are significant potential resource for electricity generation, and like crop residues have many applications, especially in developing or developed countries [11]. Bio-waste or biomass is only substitute of fossil fuels which is renewable. Bio-waste contributes greater than 6% of global non-food energy consumption, which primitive low efficiency and highly polluting combustion in poorly controlled heating and cooking fires. Bio-waste offers important advantages as a combustion feedstock due to the high volatility of the fuel and the high reactivity [11]. Bio-waste contains much less carbon and more oxygen and has a low heating value than solid fossil fuels. The burning velocity of bio-waste (pulverized) is substantially higher than that of solid fossil fuels [12].

1.2 Forms of combustion and methodology

1.2.1 Forms of combustion

Combustion is categorised in different forms such as, direct combustion, evaporation combustion, decomposition combustion, surface combustion, and smouldering combustion [13]. In evaporation combustion, the sample containing

Primary energy	Years				
	2008	2015	2020	2030	2035
Coal	3315	3892	3966	3984	3934
Oil	4059	4252	4346	4550	4662
Gas	2596	2919	3132	3550	3748
Nuclear	712	818	968	1178	1273
Hydro	276	331	376	450	476
Biomass	1225	1385	1501	1780	1957
Other renewables	89	178	268	521	699
Total	12,271	13,776	14,556	16,014	16,748

Source: www.eia.org.

Table 1.
World's primary energy demands in MTOE (metric tonne of oil equivalent).

molecular structure with comparatively low fusing temperature evaporates by heating, and reacts with oxygen in gas phase. In decomposition combustion, gases (such as H_2, CO, C_mH_n, H_2O, and CO_2) produced from thermal decomposition reacts with oxygen in gas phase, and produces flame. Usually, char or say bio-char remains after these reaction (forms of combustion) and burns by surface combustion. Smouldering combustion is the thermal decomposition at temperature lower and then the ignition temperature of volatile component of the reactive biomass samples. In industrial direct combustion of biomass, decomposition combustion and surface combustion are the main forms of the combustion [14].

1.2.2 Methodology

The following two methodologies are used for combustion:

- Qualitative comparison and
- Quantitative comparison.

The qualitative comparison is based on literature available in particular field. Combustion of different biomass materials are distinguished on the basis of the type of combustion process used.

The quantitative comparison is based on description of individually built or planned plants or industries information that suppliers and owners of biomass combustion plants have given about their efficiencies, investment costs and emissions. In quantitative comparison we prepare a model or rough information about various biomass combustion plants and further we analyse their efficiency and other characteristics.

The features of some combustion methods are shown in **Table 2**.

Combustion method	Combustion type	Features
Fixed bed combustion	Horizontal/inclined grate Water-cooling grate Dumping grate	Grate is level or sloping. Ignites and burns as surface combustion of biomass supplied to grate. Used in small-scale batch furnace for biomass containing little ash
Moving bed combustion	Forward moving grate Reverse moving grate Step grate Louver grate	Grate moves gradually and is divided into combustion zone and after-combustion zone. Due to continuous ash discharge, grate load is large. The combustion obstruction caused by ash can be avoided. Can be applied to wide range of fuels from chip type to block type
Fluidized bed combustion	Bubbling fluidized bed combustion Circulation fluidized bed combustion	Uses sand for bed material, keeps fuel and sand in furnace in boiling state with high-pressure combustion air, and burns through thermal storage and heat transmission effect of sand. Suitable for high moisture fuel or low grade fuel
Rotary hearth furnace combustion	Kiln furnace	Used for combustion of high moisture fuel such as liquid organic sludge and food residue, or large waste etc. Restricted to fuel size on its fluidity
Burner combustion	Burner	Burns wood powder and fine powder such as bagasse pith by burners, same as that for liquid fuel

Table 2.
Combustion type and feature of biomass.

1.3 Bio-waste conversion technologies

Biomass can be converted to useful products by two main processes:

I. Thermochemical process

II. Bio-chemical process

1.3.1 Thermochemical process

Thermochemical process is one of the bioenergy conversion technologies, which are used to extract energy from the biomass. Thermo-chemical conversion process can be categorized as combustion, pyrolysis, gasification and liquefaction. These processes convert the solid waste biomass into energy rich valuable products. Selection of conversion process depends upon the feedstock type and quantity of biomass, desired form of the energy, i.e., end use requirements, environmental standards and economic conditions [15, 16]. The combustion of agricultural biomass produces (800–1600°C) heat energy for electricity generation. Gasification process generates (700–1000°C) heat energy with a combustible gas mixture, commonly known as producer gas or syngas, which can be used to make synthesize fuels or other chemicals using catalysts [17]. Pyrolysis also occurs at moderate to high temperatures (450–1000°C) in the absence of oxygen to produce energy-rich liquid known as bio-oil and solid char or sometimes biochar [18]. Liquefaction processing occurs at pressure of (5–25 MPa) to prevent boiling of water in the slurry and at temperatures ranging from 200 to 500°C, depending upon whether the desired products are fractionated plant polymers [19], a partially deoxygenated liquid product known as bio-crude [20]. Liquefaction processing at modest temperatures fractionates biomass into cellulose fibres, hemicellulose dehydration products, and lignin [19].

Thus, thermochemical processing offers opportunities for rapid processing of diverse feedstocks, including recalcitrant materials, for production of fuels, chemicals, and power.

Technology	Sub-categories of Technology	Products
Combustion	• Direct combustion to produce heat	• Heat
	• Direct combustion to produce steam	• Radiant heat, hot gas
	• Co-firing	• Electrical energy
	• Co-generation	• Heat (steam), electrical energy
Pyrolysis	• Fast pyrolysis	• Bio-oil, tar, gas, solid char
	• Slow pyrolysis (carbonization)	• Char, gas
	• Flash pyrolysis	• Bio-oil, char
	• Vacuum pyrolysis	• Bio-oil
	• Intermediate pyrolysis	• Tar, gas, char, bio-oil
	• Hydro-pyrolysis	• Bio-oil
Gasification	• Steam gasification	• Gas, char, liquid residue
Densification	• Briquetting	• Briquettes
	• Pelleting	• Pellets
Liquefaction	• Hydro-thermal	• Bio-oil

Table 3.
Conversion technologies for transforming biomass into energy [22, 23].

Ravandranath and Hall [21] and Amigun et al. [22] reported that the biomass materials are converted to biofuels from which energy is extracted from it for suitable utilization. They found that there are at-least five different forms of biofuels which are in use nowadays. These are bioethanol, biodiesel, biogas, bio-methanol and biochar. Traditional technologies depend on mainly on its efficient systems such as open fires for cooking and space heating. Improved technologies are tried to increase in efficiency. Additional details on these technologies are given in **Table 3**.

1.3.2. Bio-chemical process

Gumisiriza et al. [24] reported that in bio-chemical conversion processes two main processes are used, fermentation and anaerobic digestion, together with a lesser-used process based on mechanical extraction/chemical conversion.

- Fermentation is used on a large scale in various countries to produce ethanol from sugar crops and starch crops. The biomass is ground down and then the starch is converted by enzymes to sugars; after that, yeast converts the sugars into ethanol.

- Anaerobic digestion is the conversion of organic material directly into gas, termed biogas, a mixture of mainly methane and carbon dioxide with small quantities of other gases such as hydrogen sulphide. The biomass is converted by bacteria to produce gas with an energy content of about 20–40% of the lower heating value of the feedstock.

2. Combustion properties of biomass

Combustion properties of biomass can be classified as two following properties first is macroscopic properties and second is microscopic properties [25–27]. The macroscopic properties of agricultural biomass includes ultimate analysis, heating value, moisture content, particle size analysis, bulk density, and ash fusion temperature (AFT). And microscopic analysis of agricultural biomass includes thermal analysis, chemical kinetics, and mineral data. Fuel characteristics of biomass mention above have been reported by Bushnell et al. [26]. Fuel combustion properties of biomass can be conveniently grouped into physical, chemical, thermal, and mineral properties [27].

Physical properties for combustion such as porosity, bulk density, particle size, and shape distribution are related to fuel preparation methods. Chemical properties for combustion are the ultimate and proximate analysis, gross calorific value, and heating value of the volatiles [28]. Thermal properties of combustion such as rate of combustion with burning profiles, thermal analysis (TG/DTG), and emissivity vary with moisture content, temperature, and degree of thermal degradation [29]. Thermal degradation products of biomass consist of moisture, volatiles, char and ash. The yields depend on the pyrolysis time & temperature, heating rate, feedstock type, particle size, vapour residence time, sweeping gas flow rate, atmospheric gas flow rate, and types of reactors [30]. The standard methods for analyses of biomass fuel are given in **Table 4**.

Proximate analysis has long been established for assessing the quality of coal, biomass and biochar fuels through quantifying the concentrations of moisture, ‘volatile matter’, ‘fixed C’ and ash. Proximate analysis was performed on biomass waste samples for the determination of ash, moisture, volatile matter and fixed carbon contents [11]. To determine the basic elemental composition (carbon, hydrogen, nitrogen and sulphur content) of the biomass waste samples using CHNS

Property	Standard methods
Proximate analysis	
Ash	ASTM D1102 (873 K), ASTM E830 (848 K)
Moisture	ASTM E871
Volatile matter	ASTM E 872, ASTM E 897
Fixed carbon	By difference
Ultimate analysis	
Carbon, hydrogen	ASTM E 777
Nitrogen	ASTM E 778
Sulphur	ASTM E 775
Oxygen	By difference
Heating value (gross calorific value)	ASTM D 2015, E 711
Ash elemental	ASTM D3682, ASTM D2795, ASTM D4278, AOAC 14.7

Table 4.
Standard methods of biomass fuel [11].

analyser. Oxygen content was calculated by the difference. The gross calorific value (GCV) of all studied agricultural biomass samples was determined by bomb calorific measurement.

Ash or inorganic materials in agricultural biomass depend on the type of the feedstocks and the soil contamination in which the plant grows. Ash content is an important parameter directly affecting the heating value. High ash content of a plant part makes it less desirable as fuel [31, 32]. The composition of mineral matter can vary between and within each biomass sample. The higher GCV of WC, WD and CS are owing to lower content of incombustible mineral matter (ash) and higher amount of combustible components (VM, FC, C and H) [33].

The components of biomass include cellulose, hemicelluloses, lignin, lipids, proteins, simple sugars, starches, water, and other compounds [29]. The concentration of each class of compounds varies depending on different feedstocks. Due to the carbohydrate structure, biomass is highly oxygenated with respect to conventional fossil fuels including HC liquids and coals. Typically, 30–40 wt.% of the dry matter in biomass is oxygen [30]. The lignin value in case of woody and coconut shell biomass is higher than herbaceous and agricultural biomass [34]. Heating value, which is a very important factor affecting utilization of any biomass material as a fuel, is affected by the proportion of combustible organic components (called as extractives) present in it. The heating values of the extractive-free were found to be lower than those of the extracted parts, which indicate a likely positive contribution of extractives towards the increase of heating values [29]. Lignin has higher energy content (about 30%) than cellulose and hemicellulose, because of its higher degree of oxidation [35].

As we know that some of agricultural biomasses have high contents of alkali oxides and salts, the low melting points of which may lead to various problems during combustion [36, 37]. These agricultural residues include husks, straws, stalks etc. produced after harvesting the crop. As the crop residues are normally cultivated with the aid of chemical fertilizers, these residues generally contain higher amounts of sodium/potassium compounds presents in their ash. Higher concentration of these alkali compounds result in problems like bed agglomeration, slagging on furnace walls/super heater tubes and fouling of heat transfer surfaces [38]. The successful design and operation of a fluidized bed combustor depends on the ability to control and mitigate these ash related problems [39].

3. Combustion study for biomass materials

The use of agricultural biomass as a fuel provides significant benefits in various fields as energy source as far as the environment is concerned [40]. Agricultural biomass absorbs carbon dioxide (CO_2) during growth, and emits it during combustion. Therefore, it helps the atmospheric carbon dioxide (CO_2) recycling but, it does not contribute in the greenhouse gas (GHG) effect [41]. Agricultural biomass differs from coal in many important aspects, such as the physical and chemical properties. Biomass has less carbon, more oxygen, more silica and potassium, less aluminium and iron, lower heating value, higher moisture content, and lower density and friability than coal.

At low temperatures biomass materials would be instantly ignited, when they are feed in to the high temperature furnace. Here, the pivotal factor is the moisture content is low in most biomass materials, and also can be high for some biomass materials, e.g., bagasse. Basically in the all biomass materials found the high VM contents [42]. The volatiles comprise mainly of the combustibles like as CO, H_2 and C_xH_y. These aspects show that the combustion of the volatiles would be the dominant step during the combustion process.

Kaeferstein et al. [43] state that during the batch experiments in combustion process of biomass in a bubbling fluidized bed using oxygen concentration profiles measured directly over the bed with solid electrolyte sensor. During the combustion process, he observed that there was a rapid ingestion of oxygen, which took place in one phase. Whereas, for coal, the oxygen ingestion profile exhibited in two phases; a short phase for volatile combustion and a long phase for char combustion. The combustion process of biomass was almost complete after the complete combustion of volatiles. Heat distribution analysis during the combustion of biomass showed that over 67% of their calorific values were released through the combustion of the volatiles [44].

If we talking about designing a combustor for the precise use of agricultural biomass waste, we consider the suitable parameters likes, the variability of moisture, the volatile matter content, ash content, ash composition, and the energy content of the fuel [45, 46]. Accordingly follow above statement the requirements for designing a combustor such as low moisture content (about 3–9%) and high volatile matter (about 60–80%) for high burning rate reactivity, low ash content (about

Sl. no.	Property	Biomass samples	Coal
1.	M content (wt% of dry fuel)	1–10	2–2.5
2.	Ash content (wt% of dry fuel)	0.5–22	15–18
3.	C content (wt% of dry fuel)	30–50	70–75
4.	O content (wt% of dry fuel)	30–60	5–15
5.	S content (wt% of dry fuel)	<0.5	0.5–0.9
6.	SiO_2 content (wt% of dry ash)	3.78–78.20	8–15
7.	K_2O content (wt% of dry ash)	5.34–24.70	0.2–1.0
8.	Al_2O_3 content (wt% of dry ash)	0.71–11.69	4–6
9.	Fe_2O_3 content (wt% of dry ash)	0.14–16.69	0.01–2.0
10.	Ignition temperature (°C)	155–250	490–595
11	Peak temperature (°C)	250–320	—
12.	Heating value (MJ/kg)	14–20	23–28

Source: Refs. [11, 30].

Table 5.
Comparison on physical, chemical and combustion properties of biomass materials and coal.

0.5–6%, except rice and husk materials) for less in erosion, corrosion and ash fouling problems [45]. Due to high volatile matter of studied agricultural biomass materials, they have well in heating energy.

Table 5 shows the physical, chemical and combustion properties of biomass, coal and studied biomass samples. Biomass has significantly lower heating values than most of the coals. This may be caused, due to higher moisture and oxygen content. It was also to be seen that the lower heating values lead to lower burning temperatures. Agricultural biomass also has higher volatile matter [47] than coals. Agricultural biomass usually consists of 70–80% VM whereas coal consists of 10–50% VM [48].

4. Conclusions

From above discussion, it can be concluded that the high volatile matter contents of agricultural biomass have a significant effect on the combustion mechanisms. The volatiles consist mainly of combustibles and a significant amount of energy is released during their combustion. Biomass samples have ash content less than 5%, which is much less than any other fossil fuel used for combustion processes. Range obtained for VM content i.e., 60–85% in studied biomass is as high as any of the fossil fuels [49, 50], which can initiate ignition even at lower temperature (150–250°C) and support combustion processes, whereas in other fossil fuels like coal for initiating any combustion process the required ignition temperature ranges 260–450°C. Biomass also have less in nitrogen and sulphur content than any other fossil fuels (coal), which indicates less evaluation of NOx and SOx during combustion processes [48]. These above characteristics of biomass are importance with respect to the design and operation of combustion systems for agricultural biomass. The combustion significances of the biomass composition, particularly the fuel volatility, involve changing the process of combustion [51].

An attempt has also being made in this chapter to overview and understanding the different characteristics and properties of biomass samples and to evaluate their effect on the combustion characteristics.

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