Combustion of Herbaceous and Agricultural Biomass

Crop Residues Progress and Issues Review

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Abstract

Biomass from crop residues is a potentially large source of fuel for combustion. Much of the biomass from crops is not consumed as food and is often discarded as waste or is put to other uses. It is possible to utilize the discarded biomass as fuel to produce heat in a combustion device. However, there are many potential issues associated with burning biomass. All biomass has differing chemical makeup – even if the biomass is of the same type, something as simple as production location will alter the makeup, affecting the amounts of carbon, hydrogen, nitrogen, oxygen and other trace elements. Because of these alterations in chemical makeup, direct combustion is difficult as different chemical makeup will change the combustion process, alter the energy output, and change the exhaust output. In order for crop residues to be a viable fuel source, it is critical to determine the best and most practical method of directly combusting biomass. It may be necessary to determine separate combustion techniques for different biomasses if no preprocessing is to be done. If it is possible to determine if direct combustion of crop residues is possible, this would greatly reduce the waste residues as they are typically burned off.

Key Words: Biomass, Crop Residues, Combustion

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Introduction

For thousands of years, man has used biomass as an energy source for heating and cooking. It is only in recent history that man has desired to use this resource as a way to offset his impact on the environment. Man only uses certain parts of the vegetation that is grown for food and other uses, and often the parts not consumed are discarded by burning. By using this biomass that has already been created, it may be possible to form a carbon neutral energy source that is already part of the carbon cycle. This paper will discuss the feasibility of using herbaceous and agricultural biomass as a direct combustion fuel for energy production and the issues of doing so.

Types of Biomass

When biomass is being considered, it is somewhat necessary to identify the different types available. While almost any organic matter could be considered biomass, they can be classified as natural or anthropogenic [Vassilev, et al., 2010; Vassilev, et al., 2012]. This can be broken down further into woody biomass, herbaceous and agricultural biomass, mixed biomass, animal biomass, and contaminated biomass. The herbaceous and agricultural biomass can be further broken into groups of straws, grasses, and residues. Of the types of biomass available, the herbaceous and agricultural biomass is of particular interest. Energy crops are crops specifically grown to use as biomass for energy, and are typically in the straw, grass, and woody category. Crop residues are leftover plant matter from crops grown for non-energy purposes and range from different types of straws, to nut hulls, and most anything in between.

Biomass Availability

All over the world, biomass is produced for various reasons, but mainly for sustenance. This growth is estimated to be a few hundred billion metric tons every year [Vassilev, et al., 2013A; Nguyen, et al. 2013]. The crop residues are estimated to be a few billion metric tons, which would equate to approximately 10^{16} kcal. Of these residues, it is estimated that three quarters of them are from cereal crops. While it seem to be an almost unlimited supply of biomass, some of it is already in use for other purposes than energy production, but most should be available to use. Unfortunately, because of the nature of biomass production, the biomass is not centralized for power generation, but there are options.

Combustion of Biomass

It is important to understand the combustion process in analyzing how a fuel source will perform. Combustion of biomass is a complex set of reactions, not all of which are completely known or understood [Khan, et al., 2009; Werther, et al., 2000]. During combustion, biomass begins to dehydrate, hydrolyze, and oxidize during pyrolysis to form combustible volatile compounds and reactive char. When the ignition temperature of the volatiles is reached, an exothermic reaction begins. The cellulose, hemicellulose, lignin, and resins begin to decompose and the products are stripped off into the flame zone and undergo complete and incomplete combustion. As the fuel smolders, the charring process propagates, releasing further volatiles. Solid char combustion may occur after which the fuel is fully consumed leaving only combustion products. Figure 1 shows the process in graphical form. This process is highly dependent on fuel chemical composition and combustion conditions.

Composition

In any combustion process it is necessary to understand the composition of the fuel. Biomass is difficult to determine a composition for because of the wide variety of available matter [Vassilev, et al., 2010; Vassilev, et al., 2012]. This is further complicated by no true reporting standards or criteria on what information is to be shared, as well as a lack of a consistent method of measurement. While information may be abundant, much of it has not been peer reviewed. To this end it is necessary to consult sources that report on proximate analysis, ultimate analysis, and ash analysis. These results can be seen in Table 1 for biomass. These tests show the composition including volatile matter, fixed carbon, moisture, and ash yield, as well as amounts of carbon, hydrogen, oxygen, nitrogen, and sulfur. Many other elements are found in the ash analysis, which will be discussed in its own section. Other elements found in biomass composition include calcium, potassium, silicon, magnesium, aluminum, iron, phosphorus, chlorine, sodium, manganese, and titanium. Variation of the composition of different biomasses can be attributed to several causes: species or part of plant, growth processes, growth conditions, the age of plants, use of fertilizers or pesticides, harvest time and method, and mixing of different biomasses, as well as others. When the proximate and ultimate analyses are done on a
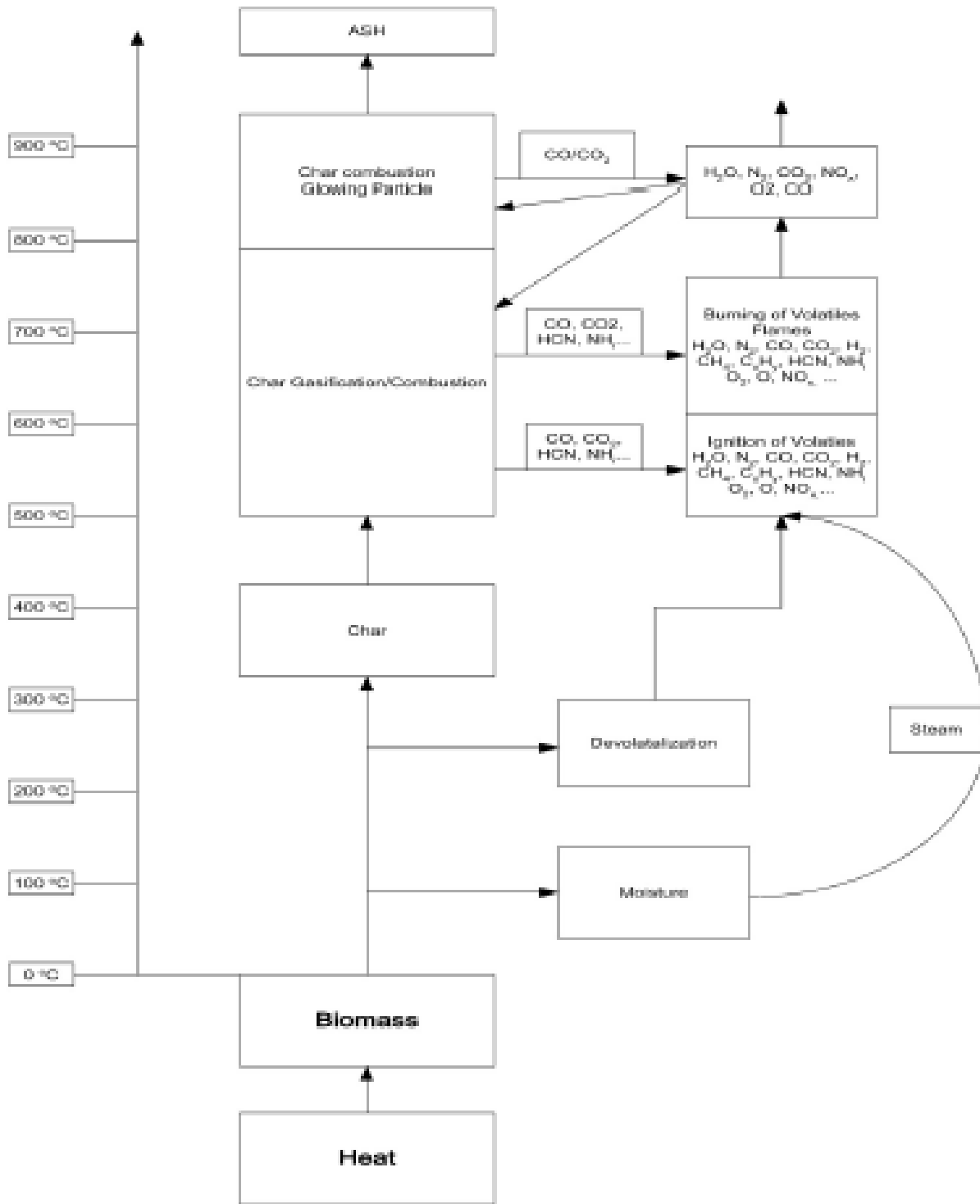
Figure 1 The typical process for combustion [Khan, et al., 2009].

Table 1 Shows the composition of several forms of biomass adapted from [Vassilev, et al., 2010].

Biomass	Proximate Analysis as measured				Proximate Analysis dry				Ultimate Analysis dry, ash free				
	VM	FC	M	A	VM	FC	A		C	O	H	N	S
Herbaceous and Agricultural Biomass													
Mean	66.0	16.9	12.0	5.1	75.2	19.1	5.7		49.9	42.6	6.2	1.2	0.15
Min	41.5	9.1	4.4	0.8	59.3	12.4	0.9		42.2	34.2	3.2	0.1	0.01
Max	76.6	35.3	47.9	18.6	85.5	37.9	20.1		58.4	49.0	9.2	3.4	0.60
Grasses													
Mean	69.0	14.1	12.6	4.3	79.0	16.2	4.8		49.2	43.7	6.1	0.9	0.13
Min	46.5	9.5	4.5	0.8	73.4	13.7	0.9		46.1	42.5	5.1	0.3	0.04
Max	73.5	16.8	42.0	9.4	81.6	18.1	9.8		52.0	44.5	6.5	2.6	0.27
Straws													
Mean	66.7	15.3	10.2	7.8	74.3	17.1	8.6		49.4	43.2	6.1	1.2	0.15
Min	58.0	12.5	7.4	4.3	64.3	13.6	4.7		48.5	40.1	5.6	0.5	0.08
Max	73.9	17.8	16.8	18.6	80.5	19.5	20.1		50.6	44.6	6.4	2.8	0.28
Other Residues													
Mean	64.6	18.6	12.4	4.4	74.0	21.0	5.0		50.2	41.9	6.3	1.4	0.16
Min	41.5	9.1	4.4	0.9	59.3	12.4	1.4		42.2	34.2	3.2	0.1	0.01
Max	76.6	35.3	47.9	16.1	85.5	37.9	18.0		58.4	49.0	9.2	3.4	0.60
Coal													
Mean	30.8	43.9	5.5	19.8	32.8	46.3	20.9		78.2	13.6	5.2	1.3	1.7
Min	12.2	17.9	0.4	5.0	12.4	20.0	5.7		62.9	4.4	3.5	0.5	0.2
Max	44.5	70.4	20.2	48.9	51.8	71.8	52.0		86.9	29.9	6.3	2.9	9.8

dry basis, without ash, the wide range of values for elemental composition narrow significantly, because biomass has a wide variation in moisture content, bulk ash yield, and inorganic content. When compared to coal, biomass is depleted in ash, fixed carbon, aluminum, iron sulfur, nitrogen, carbon, silicon and titanium, while it is enriched in moisture, chlorine calcium, hydrogen, volatile mater, potassium, manganese, magnesium, phosphorus, and oxygen.

It is not just the composition of the material that is important – the phase composition is important as well. The biomass contains organic and inorganic compounds [Vassilev, et al., 2010; Vassilev, et al., 2012]. The phase in which these occur can greatly differ, and as a result, may change the combustion characteristics of the biomass fuel. Organic matter consists of cellulose, hemicellulose, and lignin with small amount of organic minerals. The amount of each varies greatly with the type of biomass. The inorganic matter consists of silicates, phosphates, oxides, nitrates, hydroxides, sulfates, sulfites, sulfides, chlorides, and carbonates. Many of the organic and inorganic minerals are found in the mineral rich fluid within the biomass taken up by the root system, which means they are not necessarily fixed and are mobile.

Ash

Ash is a much studied component of biomass combustion, but it is not well understood [Vassilev, et al., 2010; Vassilev, et al., 2013A]. Ash forms from natural and technogenic organic, inorganic and fluid matter during the combustion of biomass and a condensed summary of major species can be seen in Table 2. It consists of inorganic crystalline and non-crystalline materials, along with organic matter in the form of char and organic minerals, as well as some liquid and gas phases of various organic and inorganic compounds. The most common elements present in ash from biomass are oxygen, calcium, potassium, silicon, magnesium, aluminum, iron, phosphorus, sodium, sulfur, manganese, and titanium. In comparison to coal, biomass ash is enriched in manganese, potassium, phosphorus, chlorine, calcium, sodium and magnesium while it is depleted in aluminum, titanium, iron, silicon, and sulfur. The composition of the ash from biomass has been found to contain more than 40 additional compounds over that of coal, as well as an increase in the trace elements. Of the compounds found in the ash silicates, oxides, hydroxides and sulfates are the most common with the formation of quartz, calcite, and sylvite. Many forms of calcium, potassium, and sodium containing compounds are not found in coal ash and is likely due to depletion of those elements. But, several compounds found in coal ash are

Table 2 Shows the major species present in biomass ash adapted from [Vassilev, et al., 2013A].

Biomass											
	SiO2	CaO	K2O	P2O5	Al2O3	MgO	Fe2O3	SO3	Na2O	TiO2	Mn
Herbaceous and Agricultural Biomass											
Mean	33.39	14.48	26.64	6.48	3.66	5.62	3.26	3.61	2.29	0.18	0.13
Min	2.01	0.97	2.29	0.54	0.10	0.19	0.22	0.01	0.09	0.01	0.02
Max	94.48	44.32	63.90	31.06	14.60	16.21	36.27	14.74	26.20	2.02	0.46
Grasses											
Mean	46.18	11.23	24.59	6.62	1.39	4.02	0.98	3.66	1.25	0.16	0.31
Min	8.73	2.98	2.93	3.14	0.67	1.42	0.58	0.83	0.09	0.01	
Max	84.92	44.32	53.38	20.33	2.59	8.64	1.73	9.89	6.20	0.28	
Straws											
Mean	43.93	14.13	24.49	4.13	2.71	4.66	1.42	3.01	1.35	0.16	0.09
Min	7.78	2.46	12.59	0.98	0.10	1.67	0.41	1.18	0.16	0.02	0.02
Max	77.20	30.68	38.14	10.38	5.57	14.10	2.82	4.93	3.52	0.33	0.28
Other Residues											
Mean	24.47	16.58	28.25	7.27	4.90	6.62	4.84	3.80	3.05	0.22	0.16
Min	2.01	0.97	2.29	0.54	0.11	0.19	0.22	0.01	0.12	0.01	0.01
Max	94.48	44.13	63.90	31.06	14.60	16.21	36.27	14.74	26.20	2.02	0.46
Coal											
Mean	54.06	6.57	1.60	0.50	23.18	1.83	6.85	3.54	0.82	1.05	0.05
Min	32.04	0.43	0.29	0.10	11.32	0.31	0.79	0.27	0.09	0.62	0.02
Max	68.35	27.78	4.15	1.70	35.23	3.98	16.44	14.42	2.90	1.61	0.18

Table 3 Shows the change in fusion temperature of ash based on initial ash formation temperature adapted from [Du, et al., 2013].

Sample	Ashing Temp	DT	ST	HT	FT
Corn Stalk					
	450	800	1098	1218	1236
	600	784	1080	1156	1270
	815	904	1100	1222	1274
	1000	995	1102	1242	1276
Wheat Straw					
	450	766	1168	1278	1320
	600	770	1170	1260	1314
	815	806	1162	1260	1326
	1000	1006	1192	1226	1300

often absent in the biomass ash. More than 60% of the ash may be water soluble, which can have advantages in cleanup and removal, but could cause issues of environmental contamination. The composition and extent of formation of ash from biomass is highly dependent on combustion temperature as significantly less ash is formed above 1000°C than at 500°C. Different fusion temperatures indicate different ash composition as can be seen in Table 3.

Given that ash is a mostly solid product, it has to be collected and cleaned from the combustion process. There is a question of what to do with the ash and many possible solutions have been presented [Vassilev, et al., 2013B]. It may be possible to utilize the ash for applications such as fertilizer and soil amendments, construction materials, adsorbents, synthesis of materials, and individual component recovery. Much of these are yet unproven as the variability of ash content raises issues, as well as unknown environmental impacts of using the ash for any application.

Slagging and Glassing

As mentioned previously, combustion at higher temperatures results in less ash formation [Vassilev, et al., 2010; Vassilev, et al., 2013A]. The cause of this is from volatilization of potassium and sodium chlorides which increases the content of magnesium, calcium, iron, aluminum, and non-metallic sulfur, phosphorus, and silicon [Du, et al., 2013; Vassilev, et al., 2013B; Vassilev, et al., 2014]. Slagging is a result of the low melting temperature of the ash. Calcium, magnesium, potassium, and sodium silicates are often found to have lower melting temperatures that when cooled form a layer of glass. With the temperature increasing, silicon dioxide content increases. When the alkali species evaporate, they can form eutectic mixtures with silicon dioxide in metal oxide forms. Ashes with more than 47% silicon dioxide content typically trap alkali metals and formed melts. Generally, the fusion temperature is reported at four different temperature measures, deformation, spherical, hemispherical, and fluid, deformation being the lowest when the material initially begins to deform and fluid being the highest when the material is a complete liquid. Peak ash production is typically near 600°C but most ash is dominated with eutectic mixtures at 1000°C. During combustion, the fusion temperatures may vary up to several hundred degrees for the ash based on the combustion temperature, and thus the likelihood of forming a eutectic mixture. Any fusion temperature below 1000°C is considered to be very low. In comparison to coal, the ash fusion temperatures

Table 4 Typical fusion temperatures for biomass ash adapted from [Vassilev, et al., 2014].

Biomass	DT	ST	HT	FT
Herbaceous and Agricultural Biomass				
Mean	797	1112	1241	1285
Min	700	795	975	1000
Max	1472	1513	1605	>1620
Grasses				
Mean	970	1127	1308	>1314
Min	700	980	1090	1000
Max	1453	1513	1550	>1586
Straws				
Mean	857	1061	1105	1214
Min	700	941	975	1025
Max	991	1180	1266	1369
Other Residues				
Mean	1023	1150	1238	>1278
Min	740	1020	1020	>1020
Max	1260	1280	1380	1500

are significantly lower. Therefore it is much more likely that glassing will occur in a biomass energy station rather than a coal energy station. By running at a temperature several hundred degrees hotter than biomass, coal is able to increase efficiency and reduce maintenance over a biomass system. The presence of certain compounds will often lower the melting point of the ash. These include diphosphorous, disodium oxide, and dipotassium oxide. Table 3 contains typical deformation, spherical, hemispherical and fluid temperatures for herbaceous biomass.

Emissions and Pollution

Biomass energy systems are often thought of as clean and non-polluting because they use naturally occurring biomass as a fuel [Vassilev, et al., 2013B; Vassilev, et al., 2014]. This is a false and disturbing viewpoint. Heavy metals are in greater abundance in biomass than in coal. These metals are from naturally occurring sources as well as from anthropogenic sources accumulated often during processing and transport. Metals such as silver, arsenic, barium, cadmium, chromium, copper, mercury, manganese, molybdenum, nickel, lead, antimony, selenium, tin, thallium, tellurium, uranium, vanadium, and zinc have all been found to occur in much greater concentration in biomass than in fossil fuels. Table 5 shows the typical amount of metals in different types of ash. What is even more concerning is that the metallic species tend to form more mobile compounds when biomass is combusted that from fossil fuels. The end position for most of these elements is in the ash but that is highly dependent on the temperature of combustion. At temperatures less than 1000°C, most of these metals with the exception of mercury appear in the ash [Vassilev, et al., 2013B; Vassilev, et al., 2014; Nzihou and Stanmore, 2013]. The mercury almost completely volatizes and leaves as a gas. The rest of the compounds then separate in different parts of the ash into either fly ash or bottom depending on their volatility at combustion temperature, with highly volatile elements attaching themselves to very fine particle. The nature of this ash presents a great issue of environmental impact as much of the compounds are water soluble. Runoff from ash can potentially contaminate surfaces, pollute water sources, and even contaminate air sheds. While the alkali pH of coal and biomass ash helps suppress solubility, the products that are soluble tend to be much more dangerous than the immobilized compounds.

Metals in ash are not the only concern for emissions and pollution. Typical combustion products of nitrogen oxides, carbon oxides, sulfur oxides, as well as particulate matter and unburned

hydrocarbons must still be addressed [Williams, et al., 2012; Cao, et al., 2008; Villenueuve, et al., 2012].

Table 5 Amount of metal in ash in mg/kg ash adapted from [Nzihou and Stanmore, 2013].

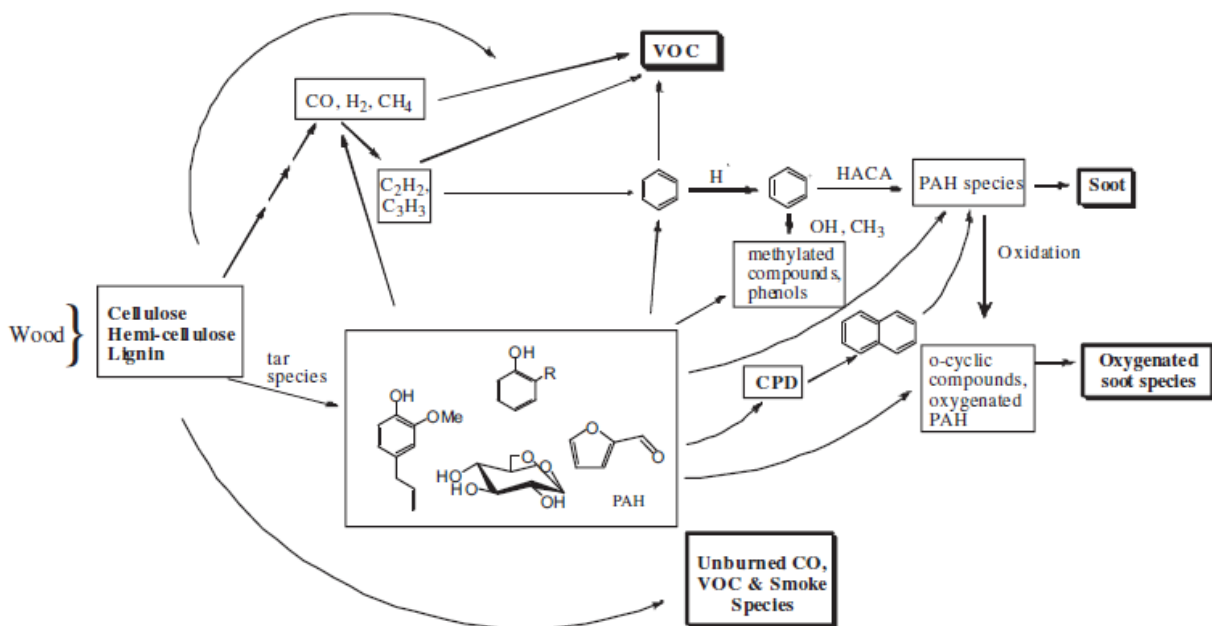| Metal	Bottom Ash	Cyclone Ash	Filter Ash	Stack Fly ash
As	51.6	32.2	12.5	3.7
Cd	6.4	47.0	36.0	10.7
Co	68.2	26.1	4.4	1.3
Cr	72.6	19.7	5.9	1.8
Cu	61.9	21.7	12.6	3.7
Fe	70.4	26.6	2.3	0.7
Mn	64.7	30.0	4.1	1.2
Ni	58.7	31.5	7.6	2.3
Pb	65.9	34.2	41.7	12.4
V	71.5	22.8	4.4	1.3
Zn	23.2	45.2	24.4	7.2
Hg	0.8	7.6	70.7	20.9

Figure 2 Shows the formation of soot and particulates from combustion [Williams, et al., 2012].

Emissions of typical combustion are highly variable based on the composition of the biomass, design of the combustor, mixing of the fuel and air, and the temperature of combustion. Particulate matter, commonly called smoke, is a combination of carbonaceous soot, aerosols, carbon monoxide, poly aromatic hydrocarbons, and char. The amount of particulate matter is mostly a function of temperature and mixing, so large scale combustion tends to have the most complete combustion, thus reducing smoke. Formation of particulates, mainly soot, can be seen in Figure 2. Nitrogen oxides form from thermal, prompt, or fuel based nitrogen reactions. Thermal and prompt oxide formations are well understood, but fuel based nitrogen can greatly affect the amount of nitrogen oxides formed in combustion. This nitrogen is typically inorganic nitrate or ammonium ion from the soil. These levels can vary based on the plant as well as the growing conditions. Sulfur is necessary for plants to function. Most of the sulfur enters via the root system as sulfate, but, biomass does not retain much sulfur and coal is likely to have greater sulfur content. During combustion, sulfur oxides are formed to varying degrees based on actual biomass type. All of these emissions are controlled based on the scale of combustion with voluntary and compulsory regulations.

Environmental Impact

Biomass production is far from being free of impact on the environment in terms of land, water, and carbon [Curtright, et al., 2012; Nguyen, et al., 2013; Singh and Kumar, 2011]. All herbaceous and agricultural biomass requires water to be produced. Depending on the region of the world, rainwater may be enough to sustain the growth rate of biomass, but in many places supplemental irrigation is needed to produce crops. This supplemental water can have varying affects on the local ecosystem, and should be considered if biomass is being produced strictly for energy and whether the water usage is worth the energy. In combustion, there will be a need for water somewhere along the line, most likely for cooling. Even if biomass is available, the extra water for the combustion process may not be available or worth the tradeoff. Most biomass for combustion is obtained from crop residues. Often, these residues may be plowed back into the soil after harvest to keep nutrients in the soil for the next crop. If the residues are removed for energy production, it may be necessary to use more fertilizer and soil amendments for the next crop. Production of these products could offset any gain in carbon dioxide offset by using biomass as an energy source as it would no longer be carbon neutral. Finally, changing the crop

species in soil also changes the carbon balance. Natural land is in balance with the carbon in the plants, soil and atmosphere. By changing to a crop, whether for food or energy production, the carbon balance changes. This may result in an increase in carbon in the atmosphere depending on the soil, plant, and management of growth.

Treatment and Pollution Controls

With any combustion process, undesired byproducts are always produced. In some cases, it is possible to prevent the problem before combustion, but often it is necessary to mitigate the issue after the fact [Vassilev, et al., 2010; 2012; 2013A; 2013B; 2014]. Pre-treatment of biomass fuel is possible by typically letting it naturally leach out minerals and dry out. This process typically consists of letting the residues remain in the field for some time while rain and other sources of water leach any water soluble compounds from the biomass. After a predetermined amount of time, the fuel can be dried. This will often result in the removal of many compounds that contribute to the ash problem by reducing the elements that cause issues. Certain hydrocarbon compounds can be immobilized in ash products be depressing the volatilization of the compound and by using clays and aluminum, calcium, magnesium sulfates, carbonates, glass, and char. Ash containing undesirable products can be leached using water as the compounds tend to be highly soluble. The ash can then be used for other purposed and the liquid can be disposed of, likely as a solid after evaporation. General power plant equipment is now capable of cleaning up most of the gaseous pollutants but it may be necessary to customize the equipment and change maintenance scheduled to deal with the different set of pollutants associated with biomass. Certain fuels may have self cleaning effects if they are enriched with zeolites, calcium, potassium, sodium, or magnesium bearing minerals, or kaolinite but it is unlikely that it will be enough to reduce pollution to acceptable levels. Slagging and glassing can be further reduced by using additives [Du, et al., 2013; Steenari, et al., 2009; Xiong, et al., 2008]. By increasing the content of alumina, magnesium oxide, and calcium oxide, the melting temperature of ash should generally increase, thus decreasing the possibility of slagging and glassing. Adding lime and kaolin can raise the melting point by a few hundred degrees, which would allow for an increase in efficiency of the power plant. Results of additives in corn stover ash can be seen in the change of fusion temperature in Table 6.

Table 6 Shows the effect of additives on increasing the fusion temperature of ash [Xiaog, et al., 2008].

		Kaolin			Calcite		
	No additive	1%	2%	3%	1%	2%	3%
DT	1170	1270	1350	1370	1170	1240	1290
ST	1180	1280	1360	1380	1190	1260	1300
HT	1200	1310	1370	1390	1210	1280	1320
FT	1230	1330	1390	1390	1220	1290	1330

Types of Combustors

Combustion of biomass can occur on a large scale or small scale. Because of this, different methods are used for combustion [Williams, et al., 2012; Gonzalez, et al., 2004; Jingura, et al., 2013]. Small scale includes domestic heating and cooking. This is often done using a small stove, but may also be done using an open fire. While not common in the developed world, it is still done in many places. A small industrial application, a testing apparatus, or heating application may use a mural boiler. This is a medium heat output device that is capable of using a heat exchanger for indirect transfer of heat, such as for home heating. Large scale applications call for the use of a pulverized fuel combustion unit, which uses pulverized fuel blown into air for combustion, a mixed or moving bed combustor which fuel is burned on a bed in air, or a fluidized bed combustor may be used in which fuel is mixed with bedding material and air is forced through the bed causing it to act like a fluid and is combusted.

Co-firing Biomass

One of the most likely uses of biomass in the near future is co-firing with fossil fuels [Vassilev, et al., 2013B; Vassilev, et al., 2014]. This plan is attractive because of its potential for lower costs and reduced solid waste and emissions while being technically feasible. These reasons seem to be a major driver in the research behind biomass fuels. Co-firing fuels is not necessarily an easy task. The composition of coal is well understood but biomass is highly variable. This variability changes combustion behavior and the different composition can result in a wide range of combustion product compositions. It is thought that co-combustion will lower carbon dioxide, ash, sulfur oxides, nitrogen oxides, and other pollutants. There is concern that the mixtures will produce mixed ashes that contain materials not present in either of the fuels which can cause difficulty in how to deal with the waste.

If a mixture of complimenting fossil fuels and biomass can be determined, it may reduce pollutants as predicted and as wanted [Vamvuka and Sfakiotakis, 2011; Wang, et al., 2014]. Experiments performed with lignite and biomass have shown that the ignition temperature of mixtures tends to be closer to the biomass temperature, likely due to the larger amounts of volatile compounds in it, while the overall combustion temperature remains closer to that of the lignite. This has lead to an improvement in both ignition and combustion performance of the

Table 7 Shows the ignition, max, burnout temperatures, as well as burnout time and ignition and combustion indices for various combinations of lignite and biomass [Vamvuka, et al., 2011].

Sample	Ti	Tmax	Rmax(10^2/min	Tb	Tb minutes	Dx10^5	Sx10^11
Lignite/cardoon 90:10	255.3	380.0	6.0	709.0	105.6	1.55	2.33
Lignite/cardoon 80:20	254.7	380.0	6.0	707.0	103.9	1.47	2.38
Lignite/cardoon 70:30	257.7	380.0	6.3	709.0	104.9	1.59	2.44
Lignite/pine 90:10	272.2	387.0	5.9	730.0	105.6	1.47	1.95
Lignite/pine 80:20	271.7	385.0	6.5	716.0	104.9	1.62	2.25
Lignite/pine 70:30	271.0	385.0	6.9	713.0	104.0	1.83	2.42

fuels by co-firing as seen by the high values of D and S the ignition and combustion indices in Table 7. The rate of ash production still remains a non-constant. With certain fuel blends the production of ash can be greatly reduced, but if the blend is off, ash production can increase as much as by half. This is especially important with herbaceous and agricultural biomass. This is likely due to the larger ash content of the biomass. It was also observed that the ash fusion temperature would decrease with such biomass but with woody biomass it would increase.

Densification

Biomass, with herbaceous and agricultural biomass in particular, is low bulk density [Gilbert, et al., 2009; Jingura, et al., 2013; Bridgeman, et al., 2008; Gonzalez, et al., 2008]. Low bulk density results in low energy density. Because of this, large quantities of biomass are needed to provide the same amount of energy as fossil fuels or even woody biomass. The large quantities can result in significant cost increases to biomass energy production from transportation costs and result in poor combustion characteristics and emissions from non-uniform energy content. To improve energy density, three methods have been popular to use: pelletization, torrefaction, and pyrolysis.

Pelletization is the simplest method to increase energy density. The biomass is squeezed into a pellet, which both removes moisture and increases its density and can be seen in Figure 3. Pelletization can be used in conjunction with torrefaction to further reduce moisture and increase density. Torrefaction is the heating the biomass in the absence of oxygen. Moisture and volatiles are driven off and can be collected to use as a gaseous fuel leaving a mild form of char. The biomass can be pelletized more easily with the moisture pre-removed. The final form of densification is pyrolysis. Pyrolysis is
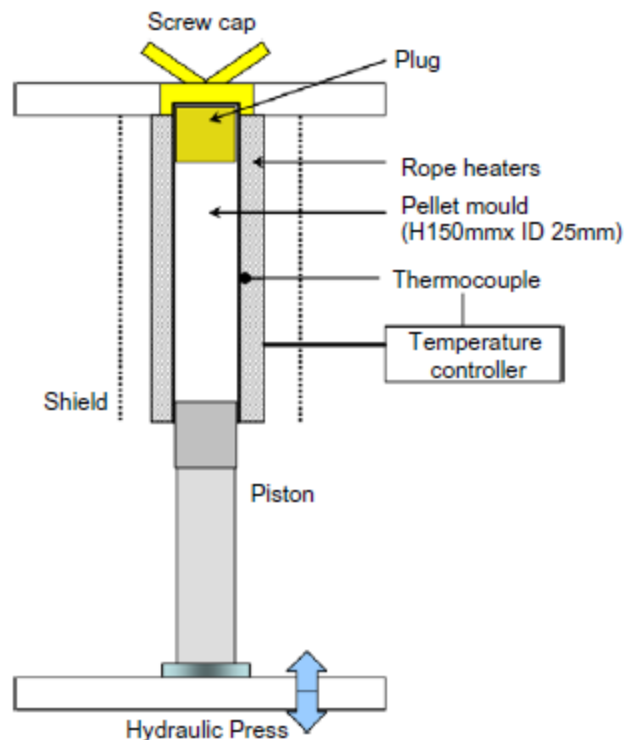

Figure 3 A pellet forming press [Gilbert, et al., 2009]

torrefaction taken to the extreme. The biomass is heated without oxygen until only char is left consisting essentially of just carbon. This is basically charcoal and is the first stage of combustion. By performing these operations it is more attractive to have a central energy plant where biomass is brought in as it reduces transportation costs and provides a higher quality fuel.

Decentralized Generation

Decentralized generation is the idea that energy should be produced in small, local plants rather than large centralized facilities. This concept may be appealing for the use of biomass given that it is usually produced on large rural land areas and in poorly developed countries [Kumar and Patel, 2011; Ozturk and Bascetincelik, 2006; Akdeniz, et al,, 2002; Valdez-Vazquez, et al., 2010; Gomez, et al., 2010]. Resource assessments have been done in several countries to look at the possibility of using decentralized energy production. Some areas already have power, but it is unreliable. Other areas are getting power for the first time. And others still are looking for a solution to increase capacity using an abundant resource but cannot afford to centralize the fuel. Many of these countries have abundant supplies of crop residues, many of which are just burned off at the end of the harvest. With decentralized generation, small plants could be located near the biomass production centers to take advantage of the waste residues.

Conclusion

Crop residue biomass is a large potential resource for carbon neutral energy. It is most attractive as it is typically a waste product, and would not contribute to increasing carbon in the atmosphere. Many issues exist with using the biomass as a combustion fuel. Some of them have been well studied, while others still need significant amount of research done before true commercialization is possible.

Recommendations

Many advances have been made in understanding the composition and combustion characteristics of herbaceous biomass. These advances have made it possible to consider using biomass on a large scale for energy production, but much work remains. Finding the right mixture of fuels, additives, and combustion temperature is critical to the success of using biomass. Work needs to continue to find a range of working parameters that can be customized

to different types of crop residues while maintaining environmental control over pollution problems associated with the use of biomass.

References

Akdeniz, R. C., Acaroglu, M., Hepbasli, A., *Energ Source* 26 (2004) 65-75.

Bridgeman, T. G., Jones, J. M., Shield, I., Williams, P. T., *Fuel* 87 (2008) 844-856.

Cao, G., Zhang, X., Gong, S., Zheng, F., *J Environ Sci* 20 (2008) 50-55.

Curtright, A. E., Johnson, D. R., Willis, H. H., Skone, T., *Biomass Bioenerg* 47 (2012) 240-249.

Du, S., Yang, H., Qian, K., Wang, X., Chen, H., *Fuel* (2013).

Gilbert, P., Ryu, C., Sharifi, V., Swithenbank, J., *Fuel* 88 (2009) 1491-1497.

Gomez, A., Rodrigues, M., Montanes, C., Dopazo, C., Fueyo, N., *Biomass Bioenerg* 34 (2010) 703-719.

Gonzalez, J.F., Gonzalez-Garcia, C. M., Ramiro, A., Gonzalez, J., Sabio, E., Ganan, J., Rodriguez, M. A., *Biomass Bioenerg* 27 (2004) 145-154.

Gonzalez, J. D., Kim, M. R., Buonomo, E. L., Bonelli, P. R., Cukierman, A. L., *Energ Source Part A* 30 (2008) 809-817.

Jingura, R. M., Musademba, D., Kamusoko, R., *Renew Sust Energ Rev* 26 (2013) 652-659.

Khan, A. A., de Jong, W., Jansens, P. J., Spliethoff, H., *Fuel Process Technol* 90 (2009) 21-50.

Kumar, M., Patel, S.K., *Energ Source Part A* 33 (2011) 2171-2180.

Nguyen, T. L., Hermansen, J. E., Morgensen, L., *Appl Energ* 104 (2013) 633-641.

Nzihou, A., Stanmore, B., *J Hazard Mater* 256-257 (2013) 56-66.

Ozturk, H. H., Bascetincelik, A., *Energ Explor Exploit* 24 (4-5) (2006) 313-330.

Singh S., Kumar, A., *Bioresource Technol* 102 (2011) 1316-1328.

Steenari, B.-M., Lundberg, A., Pettersson, H., Wilewska-Bien, M., Andersson, D., *Energ Fuel* 23 (2009) 5655-5662.

Valdez-Vasquez, I., Acevedo-Benitez, J. A., Hernandez-Santiago, C., *Renew Sust Energ Rev* 14 (2010) 2147-2153.

Vamvuka, D., Sfakiotakis, S., *Thermochim Acta* 526, (2011) 192-199.

Vassilev, S.V., Baxter, D., Andersen, L. K., Vassilev, C. G., *Fuel* 89 (2010) 913-933.

Vassilev, S.V., Baxter, D., Andersen, L. K., Vassilev, C. G., Morgan, T. J. *Fuel* 94 (2012) 1-33.

Vassilev, S.V., Baxter, D., Andersen, L. K., Vassilev, C. G., *Fuel* 105 (2013A) 40-76.

Vassilev, S.V., Baxter, D., Andersen, L. K., Vassilev, C. G., *Fuel* 105 (2013B) 19-39.

Vassilev, S.V., Baxter, D., Andersen, L. K., Vassilev, C. G., *Fuel* 117 (2014) 152-183.

Villeneuve, J., Palacios, J. H., Savoie, P., Godbout, S., *Bioresource Technol* 111 (2012) 1-11.

Wang, G., Pinto, T., Costa, M., *Fuel* 117 (2014) 269-277.

Werther, J., Saenger, M., Hartge, E.-U., Ogada, T., Siagi, Z., *Prog Energ Combust* 26 (2000) 1-27.

Williams, A., Jones, J. M., Ma, L., Pourkashanian, M., *Prog Energ Combsut* 38 (2012) 113-137.

Xiong, S., Burvall, J., Oberg, H., Kalen, G., Thyrel, M., Ohman, M., Bostrom, D., *Energ Fuel* 22 (2008) 3465-3470.