Chapter 16
Agricultural Residues from Crop Harvesting and Processing: A Renewable Source of Bio-Energy

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K.R. Hakeem et al. (eds.), *Biomass and Bioenergy: Applications*,
DOI 10.1007/978-3-319-07578-5_16,

Abstract Agricultural residues are widely used as fuel for cooking and other industrial purposes. World population increases day by day; as a result there is an increased demand of food supply to mitigate poverty and nutrition. A huge amount of biomass is obtained as residues of agricultural crops and the production of residues increases as well. Agro-residues are a renewable source of energy as the combustion products (carbon dioxide) and the energy from residue renews within a very short period of time by consuming next growing season. Entire amount of field residues cannot be used and harvested as energy because a large share of residues should be left in the field for maintaining the health of soil. However, entire amount of crop-processed residues can be utilized as source of energy. There are several technologies for converting the residues to energy. The type of residues available at specific region is an influence to the use of technology in energy conversion. The research on technologies for energy conversion is under progress at satisfactory level. The processes of harvesting and conversion of agro-residues also generate green job in different sector in the society. The success of sustainability of renewable energy from agricultural residues depends on the development of efficient conversion technology.

Keywords Renewable energy • Agricultural residue • Processing • Burning • Densification • Biogas • Gasification

16.1 Introduction

The first civilization started with agriculture on earth. Till then people cultivate crops to meet up their daily needs and other recreations. Plant is the primary accumulator for storing energy from sun capturing carbon from environment. Biomass is an important resource of energy in the world since the beginning of civilization. Agricultural crops produce large amounts of biomass residues. A large share of the crop residues are left in the field during harvesting; some could be used to produce energy. The solar energy is captured as carbon in plant through photosynthesis process; in this process, carbon dioxide (CO_2) is transformed into organic compounds, and it is the first key step for the growth of plant. The photosynthesis process is illustrated as following:

$$\text{Carbon dioxide} + \text{Water} \frac{\text{Light}}{\text{Chlorophyl}} -> \text{Carbohydrate} + \text{Oxygen.}$$

The structural block of carbohydrate (CH_2O) is the primary product for growth of plant. To fix one gram mole of carbon in the carbohydrate about 470 kJ energy from sunlight is absorbed (Klass 2004). Then the concept of using ago-residues as a source of renewable energy consists of the capture of energy from sunlight and carbon from air (CO_2) in growing plant. This biomass is transformed into other usable forms of fuel or chemicals or chemical intermediates or it is used straightforwardly as a source of heat energy.

Agricultural biomass is the greater energy potential on earth (EEA 2006). By means of existing technologies, biomass from agricultural residues can satisfy the energy demands in a wider range. Expanding demand of energy and price hike of fossil fuel and awareness on the climate change impacts are dictating an increasing demand for new types of biomass as a source of sustainable thermal energy production. Crop residues offer significant potential source of raw material to satisfy the increasing quantity. The main problem with the use of agro-residues is that they are not easy to burn due to their large dissimilarities of chemical and physical characteristics. However, progressive technical development in biomass processing and burning systems collective with further perceptiveness of strategies to get better biomass quality of herbaceous feedstock create the materialization of a potentially large new bio-energy sector.

16.2 Agricultural Residues as Potential Source Energy

Agricultural residues are indentified as a potential of biomass energy worldwide. As the residues from agricultural and forestry sources have the opportunities to be used more efficiently, several countries are giving emphasize on the development of biomass energy technology (Anonymous 1998; Li et al. 2005). Adaptation of new technologies for biomass energy conversion can reduce air pollution and net carbon dioxide emissions. Such technologies could be synthetic gas generation, liquid biofuel production, and carbon dioxide capture (Ragauskas et al. 2006). Several scenarios are to be evaluated for quantification of the potential biomass generated from agriculture. The evaluation processes include a choice of combinations of options as following (USDE 2005):

- Crop yields on active cropland.
- Ratios of grain-to-residue.
- Technological capabilities for collection of residue.
- Tillage practices for crop production.
- Crop rotation to accommodate perennial crops.
- Production of biofuels (ethanol, biodiesel, etc.).
- Residues from postharvest processing and others.

Yields of crop are of specifically important because they affect the amount of land used to meet the demand of food, feed, fiber, and other demands the amount of residue generated. Total crop production has increased significantly over last decades by two to fourfolds. Trends of major crops produced around the world are shown in Fig. 16.1. It reveals that amount of residues from agricultural produces increases as well. Oil palm fruit production is estimated to be 249.53 million tons worldwide. However, one third of oil palm fruit (93.85 million tons) was produced in Malaysia in 2012 (FAOSTAT 2014). Amount of residues not only depends on the

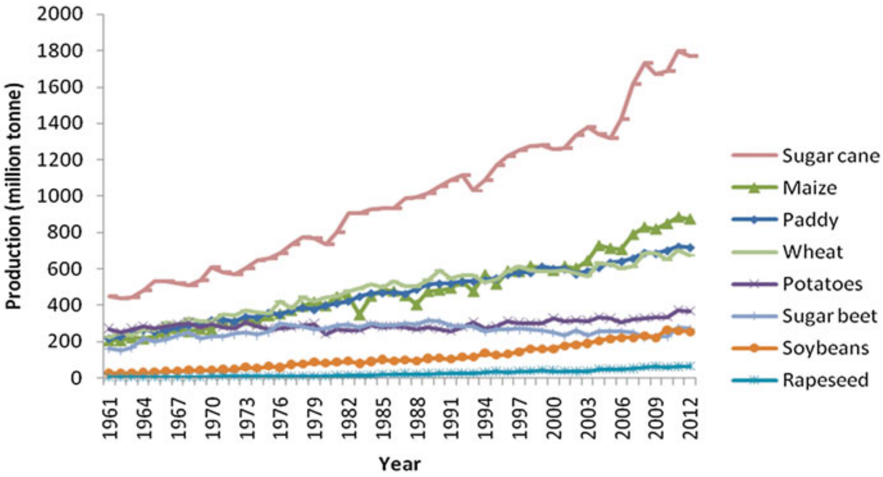

Fig. 16.1 Trends of world production of some selected crops (www.faostat.fao.org, FAOSTAT 2013)

production but also ratios of crops to residues are important factor. Ratio of crop to residues varies crop to crop (Table 16.1). A portion of entire amount of residue is recommended to leave in the field for maintaining the soil health. Moisture content of residues is another important factor that governs the actual and effective crop residue yield (Table 16.2).

16.3 Agricultural Residues from Crop Harvesting

Corn stover, cereal straw (wheat and rice straw, etc.), soybean stubble, potato stubble, and other residues are the sources of harvested residues from agriculture.

Residues from crop harvesting could potentially be converted to bio-energy, but there is a big debate regarding the harvesting rate of crop residues in a sustainable manner. Removal of residues decreases soil carbon at rate 40–90 kg carbon per hectare per year per ton of harvested residue. If the soil loss remains within allowable limits, even then the harvesting of residue arises a question of trade-offs in relation to the reduction of crop yield and reduction of nutrients of soil. The effects of the rate of residue harvesting are highly variable because it depends on local climate conditions and soil erodibility. Thus, it is problematic to recommend a single rate of residue harvest globally. In a flat land condition, a lion share of residue could be harvested sustainably for bio-energy under conservation management (Gregg and César Izaurralde 2010).

The rate of residue harvested sustainable could be decided based on a number of local conditions, for example, nutrient available in soil; organic matter exists in soil;

Table 16.1 Residue-crop ratio for different crops

Type of crops	Type of residues	Residues-crop ratio	Reference
Barley	Straw	2.25	(Kowoksing and Lapp 1975)
Cassava	Stalk	0.088	(Srisovanna 2004)
Coconut (*Cocos nucifera*)	Husk	0.419	(Koopmans 1998)
	Shell	0.12	(Koopmans 1998)
Cotton (*Gossypium hirsutum* L.)	Stalk	1.5	(Lal 1995)
		0.9175	(Allen and Musick 1972, Glover 1975)
Groundnut (*Arachis hypogaea* L.)	Straw	2.3	(Koopmans 1998)
	Straw	1.2	(Stanford Research 1976)
	Shell	0.477	(Koopmans 1998)
Jute (*Corchorus capsularis*)	Stalk	3.0	(Koopmans 1998)
Maize (*Zea mays* L.)	Stalks	2.0	(Koopmans 1998)
	Stalks	1.07	(Arnold 1975, Dugas 1973)
	Cob	0.273	(Koopmans 1998)
	Husk	0.2	(Koopmans 1998)
Oats	Straw	2.5	(Kowoksing and Lapp 1975)
Oil palm	Empty bunches	0.428	(Srisovanna 2004)
	Fiber	0.147	(Srisovanna 2004)
	Shell	0.049	(Srisovanna 2004)
	Frond	2.604	(Srisovanna 2004)
	Male bunches	0.233	(Srisovanna 2004)
Potato (*Solanum tuberosum*)	Straw	0.25	(Lal 1995)
Rice (*Oryza sativa* L.)	Straw (Local variety)	1.697	(Yokoyama et al. 2000)
	Straw	1.4	(Kowoksing and Lapp 1975)
	Straw (high yielding variety)	1.05	(BRRI 1996, 1997)
	Husk	0.20	(www.knowledgebank.irri.org)
	Bran	0.083	(Koopmans 1998)
Rapeseed (*Brassica napus*)	Stalk	1.5	(Lal 1995, Lal 2005)
Rye	Stalk	2.25	(Kowoksing and Lapp 1975)
Sesame(*Sesamum indicum*)	Stalk	1.5	(Ahiduzzaman 2011a)
Sorghum	Stover	1.07	(Allen and Musick 1972, Allen et al. 1975)
Soybean	Straw	0.85	(Stanford Research 1976)
Sugarcane (*Saccharum officinarum*)	Top	0.3	(Koopmans 1998)
	Bagasse	0.29	(Koopmans 1998)
Sunflower	Stover	5.0	(Stanford Research 1976)
Vegetables	Residues	0.4	(ICCEPT 2005)
Wheat (*Triticum aestivum*)	Straw	1.5	(Lal 1995)
		2.75	(Allen and Musick 1972, Allen et al. 1975)

Adapted from Ahiduzzaman (2011a)

Table 16.2 Moisture content of different agro residues

Agro residues	Moisture content percentage by mass	Reference
Rice straw	12.7	(Yokoyama et al. 2000)
Wheat straw	9.2	(Koopmans and Koppejan 1997)
Maize stalks	11.11	(Koopmans and Koppejan 1997)
Sugarcane top	50.0	(Koopmans and Koppejan 1997)
Jute stalk	9.5	(Ahiduzzaman 2011a)
Groundnut straw	12.1	(Koopmans and Koppejan 1997)
Rapeseed stalk	7.5	(Hossain and Badr 2007)
Sesame stalk	9.5	(Hossain and Badr 2007)
Cotton stalk	12.0	(Koopmans and Koppejan 1997)
Vegetables	20.0	(ICCEPT 2005, Hossain and Badr 2007)
Potato	12.0	(Ahiduzzaman 2011a)
Rice husk	10	(Ahiduzzaman 2011a)
Rice bran	14.9	(Qingci et al. 1999)
Maize cob	15	(Hossain and Badr 2007)
Maize husk	11.1	(Koopmans and Koppejan 1997)
Bagasse	49	(Yokoyama et al. 2000)
Groundnut shell	8.2	(Koopmans and Koppejan 1997)
Coconut husk	10.3	(Koopmans and Koppejan 1997)
Coconut shell	8.7	(Koopmans and Koppejan 1997)

effects of wind and runoff on soil erosion; moisture content of soil; crop yield; and the cost of harvesting. An estimate recommended that 2–3 tons/acre of residues after harvesting should be remained in the field for maintaining the good soil health (NebGuide 2012). Several studies examine the rate of residue removal considering different practices of management and soil conservation programs; soil coverage by the residues left in the field after harvest. McCool et al. (1995) showed that it is not linearly related that after 30 % of residue removal 70 % of land is covered, regardless whether the land coverage is measured. They measured that a 30 % removal of residue resulted in 93 % of soil coverage after harvest (Fig. 16.2). The relationship between land covered by the residue and the amount of residues removed will differ with respect to different crop and yield data. Therefore, it is recommended to determine the appropriate removal rate of residue for a particular crop at particular location (USDA 2006).

Soil organic matter content is important to allow proper nutrient supply and to maintain physical properties of soil that are essential for soil health, water infiltration rate, and soil water-holding capacity. Harvest efficiency of agro-residues depends on several aspects as following:

- Time of residues collection depends on grain harvesting period.
- Amount of traffic on crop residues during harvesting of grain.
- Water content in soil and standing water on soil surface and any natural calamity during the crop harvest and after the harvest as well.
- Type of harvesting machinery used.

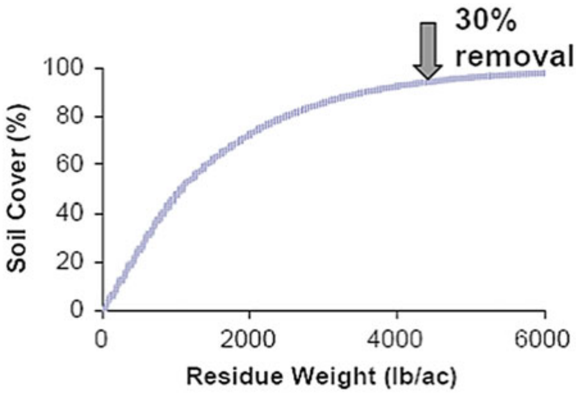

Fig. 16.2 The relationship between percent of soil covered by residues after harvest and residue weight per acre for common small grains and annual legumes in the non-irrigated U.S. Northwest (McCool et al. 1995)

16.4 Residues from Crop Processing

Residues from crop processing are generally all dry, uniform in quality. Types of residues from crop processing typically vary based on the available crop processed in certain location. In Canada, the main crop milling residues are wheat bran, oat hulls, corn cobs, barley hulls, and sunflower hulls being commercially developed for bio-heating. The quantity of residues obtained from grain processing in Canada was estimated at 1.5 million tons approximately (Samson et al. 2006). Presently, there is a rising competition for grain milling residues between the bio-fiber pellet fuel and feed industry for livestock. Rice husk is another milling by-product from rice-processing industries. Total potential production of residues from crop processing can be easily estimated from the total production data shown in Fig. 16.1 multiplied by the residues ratio shown in Table 16.1. For example, world rice husk production potential is approximately 132 million tons. Rice husk has very good properties as biomass fuel for producing steam and other process heat, e.g., crop drying as well. World bagasse production is estimated to be 531 million tons in 2012. In Malaysia, total production of empty fruit bunches and fruit shell of the oil palm was 40.17 and 4.60 million tons, respectively (FAOSTAT 2014).

16.5 Physical, Chemical, and Thermal Properties of Agricultural Residues

Moisture content of residues is another important factor that governs the actual and effective crop residue yield (Table 16.2). The moisture content of agro-residues varies widely from 8.2 to 49 % by mass. Calorific value of a biomass depends on percentage of cellulose, hemi-cellulose, and lignin. Higher amount of ash lower the calorific value of biomass. Net calorific value is also affected by inherent moisture content of residues. Calorific values of some typical residues are shown in Table 16.3.

Table 16.3 Calorific value of different agricultural residues

Type of crops	Calorific value (GJ/ton)	Reference
Barley straw	16.94	(Kowoksing and Lapp 1975, Green 1975)
Cassava stalk	18.42	(Srisovanna 2004)
Coconut husk	18.62	(Koopmans 1998)
Coconut shell	18.10	(Koopmans 1998)
Cotton stalk	12.38	(Koopmans 1998)
Cotton field trash	16.25	(McCaskill and Wesley 1976)
Groundnut shell	15.66	(Koopmans 1998)
Groundnut straw	17.58	(Koopmans and Koppejan 1997)
Jute stalk	16.91	(Hossain and Badr 2007)
Maize cob	16.23	(Koopmans 1998)
Maize husk	12.38	(Koopmans 1998)
Maize stalks	16.80	(Koopmans 1998)
Oats straw	17.40	(Kowoksing and Lapp 1975, Green 1975)
Oil Palm		
Empty bunches	17.86	(Srisovanna 2004)
Fiber	17.62	(Srisovanna 2004)
Shell	18.46	(Srisovanna 2004)
Frond	9.83	(Srisovanna 2004)
Male bunches	16.33	(Srisovanna 2004)
Potato	17.35	(Hossain and Badr 2007, ESTU 1999)
Rapeseed stalk	16.50	(Kordas and Bojanowska 2010)
Rice bran	13.97	(Koopmans 1998)
Rice husk	12.6–15.19	(Ahiduzzaman 2011a)
Rice straw	16.30	(Yokoyama et al. 2000)
Rye stalk	17.40	(Kowoksing and Lapp 1975, Stanford Research 1976)
Sesame stalk	15.92	(Cuiping et al. 2004)
Sorghum straw	13.93	(Green 1975)
Soybeans straw	16.25	(Stanford Research 1976)
Sugarcane bagasse	18.10	(Koopmans 1998)
Sugarcane top	15.81	(Koopmans 1998)
Sunflower stalk	18.57	(Stanford Research 1976)
Vegetables	13.00	(ICCEPT 2005, Hossain and Badr 2007)
Wheat straw	15.90	(Koopmans and Koppejan 1997)

16.6 Conversion of Agricultural Residues to Energy

Most common way of conversion of agro-residues is burning process. The heat energy is generally used directly for cooking, parboiling process, heating buildings, drying of crops, and processes heat in the industry. It could be used as source energy for producing steam as well as generating electricity. Agricultural residues could be transformed into liquids or gases fuel. They are suitable for running electric generator or automobile transportation. Ethanol fuel is produced through typical fermentation and distillation process. Residues also can be transformed into a gas by pyrolysis process under low oxygen condition in a reactor.

Animal dung can be transformed into biogas through an anaerobic digestion process. The biogas is burned to produce heat, steam, or electricity. Extra pure methane gas can be obtained from biogas by removing carbon dioxide and sulfide gas. Technological innovation of advanced applications of biogas is still in development process. Direct combustion of biogas is very old fashion; however, it is a promising technology to run advanced gas turbine and produce electricity. The efficiency of this system is higher by twofold as direct combustion of raw biomass to generate electricity from steam. Biogas obtained from residues also can be converted into hydrogen fuel or liquid methanol, which also can be transformed through chemical process to electricity in an advanced and efficient fuel cell (USDE 2002).

16.6.1 Direct Burning of Agricultural Residues

Direct burning of biomass is traditional way of biomass conversion technology. Cook stove is used to burn biomass in rural household and small restaurant. The thermal efficiency of traditional stove is very low, sometimes less than 10 %. However, a lot of improved cook stove (ICS) programme has been implemented worldwide to reduce pollutions. In agro-processing industry, boiler is run by direct combustion of residues.

16.6.2 Densification of Agricultural Residues

A large quantity of agricultural residues are produced and used in inefficient manner in many developing countries causing contamination to the environment. The most common agricultural residues are straws of wheat and rice, rice husk, coffee husk, sugarcane bagasse, jute sticks, groundnut shells, mustard, and cotton stalks. Sawn waste, a milling residue of timber, is also available in a large quantity. Difficulties arise during the transportation, long time storage, and handling. The bulky residues also create problems during direct burning in conventional stoves or furnace in association with very low combustion efficiencies and air pollution. The energy conversion efficiencies of residues are as low as 20–40 % in association with incomplete combusted carbon in the form of carbon monoxide in excess of 10,000 ppm in flue gas and the particulate matter emissions in the flue gases in excess of 3,000 mg/Nm^3 (Grover and Mishra 1996; Ahiduzzaman et al. 2009). In addition, a large amount of unburnt carbonaceous ash needs to be disposed of. Biomass briquetting pelleting could solve these problems and could provide the important domestic and/or rural industrial energy. Densification/compaction of loose biomass is known as briquetting or pelleting of sawdust and any other agricultural residues. The technology for biomass briquetting is adapted and practically using for many years in several countries. The screw extrusion technology for biomass briquetting was first invented and developed in Japan in 1947. There are some other densification processes such as the “Prest-o-log” technology developed in the United States, the “Compress” method in West Germany, and the “Glomera” method in Switzerland.

Table 16.4 Properties of densified biofuel

Bulk density of raw material (husk), kg/m^3	117.0
Bulk density of densified fuel, kg/m^3	825.4
Apparent density of densified fuel, kg/m^3	1219.0
Bulk compaction ratio	7.01
Nominal length of fuel, cm	60–100
Nominal diameter, cm	5.6–6.0
Inner hole diameter, cm	1.8–2.4
Calorific value of raw rice husk, MJ/kg	13.50
Calorific value of rice husk briquette, MJ/kg	15.20

Source: Ahiduzzaman (2006), Ahiduzzaman (2011a)

The bulky and loose waste biomass materials are transformed into solid biomass fuel by compression process or commonly known as briquetting process. The most commonly used briquetting process in the developing countries is screw press briquetting or screw extrusion process. Compression ratio of biomass briquette ranges from 2.5: 1 to 8.25:1 or might be more (Moral and Rahman 1999; Ahiduzzaman 2007; UNEP 2009). For instance, some properties of briquette fuel from rice husk are shown in Table 16.4. The biomass briquette fuel has also a social impact in gender issues and employment generation. Time savings for cooking fuel collection by women in rural area is estimated to be 12 man-day per year if the briquette fuel is used. Another important issue is that green job creation by briquette process in rural area is estimated to be 3.73 man-day/ton of briquette production (Ahiduzzaman 2011b).

16.6.3 Biogas Production from Agricultural Residues

Biogas is a product produced in anaerobic digestion phenomenon by which organic matter is transformed into methane (CH4) in the absence of air (oxygen). Biogas is produced naturally from the anaerobic digestion of biomass in such situations as wet rice fields, ponds, or marshes. Methane released from microbial activity is estimated about 590–880 million tons into the atmosphere worldwide. About 90 % of the Methane emitted from biogenic sources contributes approximately 90 % of global methane emission. The rest is derived from fossil origin. Concentration of methane is estimated to be 1.65 ppm in troposphere of northern hemisphere. Global warming potential of methane is 21 times more than that of carbon dioxide (Uwe Rehling 2001). Trapping the biogenic methane by producing biogas is the solution of reducing global warming effect. The methane gas yield potential from various types of agro-residues is shown in Table 16.4. Using this factors biogas potential can be estimated for a certain region based on the amount and type of residues.

Biogas consist of a large number of complex microbe species involves in biogas production process those act in a different way, remarkable the methane-producing microbes. The whole process of biogas production is divided into three different footsteps: hydrolysis, acidification, and finally the methane production. Three types of species of bacteria are involved here.

Table 16.5 Methane yields of some selected agro residues in milliliter per gram volatile solid (VS) added

Source of agro residues	Particle size (mm)	Methane gas yield, mL/g VS_{added}	Reference
Barley straw	50–100	229	(Dinuccio et al. 2010)
Cotton stalks		145	(El-Shinnawi et al. 1989)
Maize stalks		229	(El-Shinnawi et al. 1989)
Oats	<20	250–260	(Kaparaju et al. 2002)
Potato		390	(Buffière et al. 2006)
Rapeseed straw		240	(Lehtomäki et al. 2008)
Rice straw	50–100	195	(Dinuccio et al. 2010)
Rye straw	<2	360	(Petersson et al. 2007)
Sorghum whole plant	20–40	362	(Bauer et al. 2010)
Sugarcane residue	1	177	(Nzila et al. 2010)
Sunflower whole plant	20–40	345	(Bauer et al. 2010)
Wheat straw	10	299–331	(Hashimoto 1989)

Firstly, in the fermentation process, bacteria break the longer chains of the complex molecules of carbohydrate, protein, and lipid into smaller molecules. For instance, polysaccharides are transformed into monosaccharide. Proteins are broken into amino acids and peptides.

Secondly, bacteria are responsible for acid production and convert the intermediate products obtained from fermentation step into acetic acid (CH_3COOH), carbon dioxide (CO_2), and hydrogen (H_2). These bacteria involved in acidification are facultatively anaerobic and have the ability to grow in acidic conditions. They consume carbon and oxygen to generate acetic acid. In this process, they consume the dissolved oxygen in the solution or the oxygen bounded in other molecule. Hereby, the bacteria involved acid production to ensure an anaerobic environment which is necessary for the microorganisms involved in methane production. Moreover, in this process the compounds are reduced with a lower molecular weight into organic acids, carbon dioxide, alcohols, hydrogen sulphide, amino acids, and traces of methane.

Finally, methanogenic bacteria decompose the compounds with a lower molecular weight. In the last step, the microbes utilize acetic acid, carbon dioxide, and hydrogen to generate methane and carbon dioxide. Under natural conditions, methanogenic bacteria occur under natural condition to the point that anaerobic situations are provided, such as under water (e.g., wet paddy field, marine sediments, etc.), in ruminant stomach, and in marshes. The yield potentials of methane gas from some typical biomass residues are furnished in Table 16.5.

16.6.4 Biomass Gasification

Biomass gasification means incomplete combustion of biomass resulting in production of combustible gases consisting of carbon monoxide (CO), hydrogen (H_2), and traces of methane (CH_4). This mixture is called producer gas. Producer gas can be used to run internal combustion engines (both compression and spark ignition), can be used as substitute for furnace oil in direct heat applications, and can be used to produce, in an economically viable way, methanol—an extremely attractive chemical which is useful both as fuel for heat engines as well as chemical feedstock for industries. Since any biomass material can undergo gasification, this process is much more attractive than ethanol production or biogas where only selected biomass materials can produce the fuel.

16.7 Conclusion

Wide varieties of agricultural residues are produced worldwide. Production of agro-residues increases over time due to the intensive increased food production to mitigate poverty and nutrition. Agro-residues are a renewable source of energy. Entire amount of residues cannot be used as energy because a large share of residues should be left in the field for maintaining the health of soil. Maximum 35 % of field residues can be harvested for energy purposes depending on the local condition. However, entire amount of agro-processed and agro industrial resides can be used as energy. Physical, chemical, and thermal properties are different for different source of resides. There are several technologies for converting the residues to energy. The technological aspects could be varied based upon the type of residues available at certain locality. Advanced and modern technologies are under development and the progress is satisfactory. Therefore, more usable energy could be harvested from conversion process of agro residues which ensures the sustainability of renewable sources of energy from agro residues in future.

Acknowledgments The authors are thankful to university authority for their financial support. The project is financed by the Universiti Kebangsaan Malaysia, under the Grants UKM-AP-2012-008 and UKM-DPP-2013-108.

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