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Review

Challenges and opportunities of lignocellulosic biomass for anaerobic digestion

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ABSTRACT

Global annual production of lignocellulosic biomass including undervalued agricultural residues and greenhouse biomass is about 181.5 billion tonnes. This undervalued biomass has a high potential to produce biogas in anaerobic digestion (AD). Among the various pre-treatment methods, hydrothermal (HT) pre-treatment of lignocellulosic biomass is a promising approach to increase biogas production in AD. However, the high carbon to nitrogen ratio (C/N) of lignocellulosic biomass is reported to be the major limiting factor for a higher biogas yield. Hence, the synergistic integration of low C/N ratio biomass with high C/N ratio lignocellulosic biomass in an AD system appears to be a logical option to enhance biogas yield. High moisture lignocellulosic biomass HT pretreatment and biogas production in AD have the potential for renewable energy production with limited use of process energy. However, hydrothermal process temperature, AD substrate C/N ratio and its inhibitory elements are important parameters for optimum biogas production. Greenhouse biomass pretreatment in hydrothermal process can produce biochar, biogas and biofertilizer, which can be used as input heat and nutrient source for greenhouses. Finally, the operation of greenhouse in this system can manage zero waste and reduce greenhouse gas (GHG) emissions and climate change.

1. Introduction

Lignocellulosic biomass is currently an undervalued biomass but it has a high potential for biogas production. Present energy research trend focuses on production of alternative energy to mitigate environmental pollution from traditional energy (Elsharnouby et al., 2013). Anaerobic digestion (AD) is the least energy-consuming process among all bioenergy production technologies with GHG emission reduction benefit (Hamawand, 2015). Lignocellulosic biomass such as agricultural residues (crop residues), wood and grass are promising sources of alternative energy (Hu and Ragauskas, 2012). Global annual production of lignocellulosic biomass is about 181.5 billion tonnes, which is an abundantly available bio-resource (Kumar et al., 2008). USA alone produces about 1.25 billion tonnes of lignocellulosic biomass annually where 30% is forest biomass (Limayem and Ricke, 2012). It was estimated that sustainably harvestable agricultural residual biomass in 2014 in Ontario would be 22.5 million tonnes (Hewson, 2010) where 12.78 million tonnes is agriculture crop residue. The estimated annual agricultural crop residue in Canada is 69.25 million tonnes, where 18.44% is in Ontario (OFA, 2013). In Canada corn, wheat, barley, canola, oats and soybean crop residue are 19.40%, 32.67%, 17.89%, 14.25%, 7.65% and 4.39%, respectively of the total crop residue. But about 62% of Ontario crop residue is corn residue (OFA, 2013).

Greenhouse biomass is also known as lignocellulosic biomass, which is the same as other agricultural crop biomass. In Ontario, 928,000 t of greenhouse biomass was produced in 2009 (Hewson, 2010). According to the Canadian Encyclopedia online report of 2015, greenhouse crop production is emerging to reduce imported foods and meet consumer's demand for fresh and healthy food in Canada (Dorais et al., 2015). Public and private research centers such as the Agriculture department, Agrifood Canada, Universities etc. are growing new varieties of different crops in greenhouses in a controlled environment. In 2014 Greenhouse crop surface land area in Canada was more than 2000 ha of which 1044 ha was in Ontario, 493 ha was in British Columbia, 235 ha was in Quebec and 116 ha was in Alberta. In 2014, about 44% of greenhouse crop lands grew vegetables, such as tomatoes (21.6%), cucumbers (11.2%), peppers (10.8%) and lettuce (0.5%). The rest of greenhouse land areas (56%) were used for agricultural, horticultural and forest plants. Greenhouses are increasing due to the increasing food supply throughout the year in Canada and their heating cost is the highest operating cost to producers. In greenhouses, heat is supplied from non-renewable fossil fuels such as oil and natural gas with high cost and environmental impact. Therefore, several greenhouses switched to biomass burning as an alternative source, which again needs extra capital investment (BioFuelNet, 2014). Till now, management of greenhouse biomass/residues through anaerobic digestion is rare in

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literature but it has the opportunity to change natural gas heating by biogas and apply digestate as nutrient to greenhouse crops if technology becomes available. Therefore, this paper is an attempt to summarize the challenges and potential pre-treatment methods of lignocellulosic biomass including greenhouse residues to produce biogas through anaerobic digestion techniques. This paper also addresses inhibitors of anaerobic digestion, their mitigation approaches and limit of inhibition for safe anaerobic digestion treatment of lignocellulosic biomass. Lignocellulosic biomass co-digestion with other substrates is also addressed to enhance biogas production. The knowledge about biogas production quality and quantity may encourage different biomass handling industries to produce renewable energy as well as GHG reduction.

2. Composition of lignocellulosic biomass

Lignocellulosic biomass is an alternative energy source, which is available to produce biofuels in North America. Wood, grass, agricultural residues, energy crops and forest residues are all types of lignocellulosic biomass (Hu and Ragauskas, 2012). Most of the plants are composed of three major components namely cellulose (38–50 %), hemicellulose (23–32 %), and lignin (10–25 %) (Sawatdeenarunat et al., 2015). Average values of these components of biomass used for biofuel production are shown in Table 1.

Cellulose fibers are stabilized laterally by hydrogen bonds which stay between hydroxyl groups and produce linear chains. Cellulose chains are stiffened by hydrogen bonds and a crystalline structure is aggregated (Pu et al., 2008). Hard wood contains higher amounts of cellulose than soft wood. Cotton fibers are simple example of cellulose (Kumar, 2010; Kambo, 2014). Hemicellulose is complex structure of carbohydrate with different types of polymer e. g. the second most common polysaccharides in nature (Saha, 2003). Unlike cellulose, hemicellulose is composed of combinations of pentoses and/or hexoses and glucose. The source of hemicellulose determines its chemical nature and in general, xylan is the dominant hemicellulose component of agricultural plants, such as grasses, straws and hardwoods (Pu et al., 2008; Kambo, 2014). Lignin is a phenolic polymer in lignocellulosic biomass and when enzyme needs to act on the carbohydrate fraction of a lignocellulosic biomass, it creates a physical barrier (Hu and Ragauskas, 2012). Softwoods contain a higher composition of lignin compared to hardwoods. Lignin provides structural strength of a plant and protects it from microbial attack.

Table 1
Composition of lignocellulosic biomass.

Biomass name	Composition (%, dry basis)			C/N ratio	References
	Cellulose	Hemicellulose	Lignin		
Rice straw	35–44	27–34	12–13	47–67	1, 2, 3, 4, 5
Cotton straw	42	12	15	–	6
Cotton stalk	31	11	28	41	7, 8
Wheat straw	38–42	20–27	20–22	50–60	1, 3, 4, 5, 9
Soybean straw	38	16	16	50	6, 10
Barley straw	38–48	21–25	11–26	71	5, 6, 10
Oats straw	33	23	21	95	6, 11
Alfalfa straw	31	10	10	47	6, 12
Rape seed straw	37	25	17	28	11, 13
Corn stover	40	25–31	14–17	50–63	1, 3, 4, 14
Corn cobs	45	25	15	123	10, 15
Sugarcane bagasse	40–45	20–24	25–30	118–150	1, 3, 4, 14
Poplar	45	21	24	103	10. 16
Pine	25–44	26–32	28–48	140	1, 6, 10
Red maple/oak	39	33	23	250	6, 10
Spruce	28–43	20–30	28–35	170	1, 6, 10
Soft wood stem	40	30	30	511	15
Switchgrass	36–45	28–30	12–26	90	1, 3, 14
Miscanthus	38–48	19–30	12–25	77	1, 5, 17, 18
Pea vines	40	10	9	120	6, 10
Green bean	17	16	8	11	19, 20
Grape stem	–	–	12	59	6, 21
Tomato pomace	39	5	11	–	6
Tomato plant	39	29	12	35	22
Cucumber plant	17	17	3	11	19, 20
Pepper plant	18	12	8	13	19, 21

1 = OFA (2013); 2 = Sun et al. (2005); 3 = Karthikeyan and Visvanathan (2012); 4 = Divya et al. (2015); 5 = Sawatdeenarunat et al. (2016); 6 = Cornell composting (2015); 7 = Silverstein et al. (2007); 8 = Munir et al. (2009); 9 = Silva and Rouau (2011); 10 = Saidur et al. (2011); 11 = Lehtomaki et al. (2008a, 2008b); 12 = Sawatdeenarunat et al. (2015); 13 = Díaz et al. (2010); 14 = Saha (2003); 15 = Chandra et al. (2012a, 2012b); 16 = Sannigrahi et al. (2010); 17 = Hodgson et al. (2011); 18 = De Jong et al. (2003); 19 = Callejón-Ferre et al. (2014); 20 = Callejón-Ferre et al. (2011); 21 = Masiá et al. (2007); 22 = Font et al. (2009)

Table 2
Growth of AD in Europe and North America (CBA, 2017; ABC, 2017; EBA, 2016).

Country/ Province	Number of installed AD in operation								
	2012			2014			2016		
	Farm	Other	Total	Farm	Other	Total	Farm	Other	Total
Ontario	4	8	12	35	9	44	36	35	71
Canada	13	117	130	47	120	167	51	135	186
USA	192	1828	2020	239	1877	2116	259	1953	2212
Europe	–	–	13812	–	–	17240	–	–	17358
Germany			8700			10786			10846

3. Growth of AD plants in North America and Overall

Installation of AD plants has increased rapidly in Ontario since 2012 as a result of the introduction of the feed in tariff (FIT) program for farm level electricity production in combined heat and power (CHP) system. The growth of biogas plants in North America and Europe is shown by number in Table 2. There were only 4 AD plants in Ontario until 2012, which was rapidly increased to 35 in 2014 and 36 in 2016 at farm level due to the introduction of FIT in 2013. Ontario government changed policy to allow farm ADs to use up to 50% off-farm substrate in 2013. Now farmers have the opportunity to earn 20 $ t^{-1} to 50 $ t^{-1} extra for receiving tipping fee from off-farm substrates. At present, the city of Toronto of Ontario pays about 120 $ t^{-1} to landfill owners as a tipping fee for their waste diversion. This data was collected during a visit of Toronto AD plant. Until the end of 2016, the total number of AD installed in Ontario was 71 whereas it was 186 in Canada. In USA and Canada, AD is mostly used for manure treatment at farm and municipal waste water treatment. In Europe, the number of installed AD in 2012 was 13812 of which 8700 was in Germany. This number was increased to 17358 in Europe and 10846 in Germany in 2016. Several AD plants are used for landfill gas mitigation purposes. Only one municipal food waste processing wet mesophilic AD plant is being operated in North America and it is in Toronto, Canada.

Food waste co-digestion with manure is being encouraged in farm AD to use its extra capacity, existing infrastructure and expertise. Farm ADs in Ontario are now receiving tipping fee and FIT benefit. Opportunity has been created for farm AD owners to produce renewable energy by receiving carbon credit in Canada, Europe, and USA. Asian and African countries use limited number of industrial sized (about 10,000 m^3 volume) biogas plants but they are using small scale locally built biogas plants for cooking and other household purposes. China, India and Nepal started national biogas program around 1950 and by 2009 they had about 17 million, 12 million and 190 thousand biogas AD plants made of masonry materials of 4 m^3 to 10 m^3 volume (Fulford, 2017). The African Biogas Partnership Program built 3660 biogas plants in Africa from 2009 to 2015 using the technical assistance of the Netherlands Development Organization (Berhe et al., 2017). According to the report of Subedi, P.S. (2013) of Winrock International, Bangladesh built 23611, Pakistan built 2097, Indonesia built 5572,