Biotechnology Advances 34 (2016) 1289–1304

Contents lists available at ScienceDirect

Biotechnology Advances

journal homepage: www.elsevier.com/locate/biotechadv

Research review paper

Anaerobic digestion of straw and corn stover: The effect of biological process optimization and pre-treatment on total bio-methane yield and energy performance

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A R T I C L E   I N F O

Article history:
Received 21 June 2016
Received in revised form 14 September 2016
Accepted 26 September 2016
Available online 30 September 2016

Keywords:
Anaerobic digestion
Biomethane
Chemical pre-treatment
Corn stover
Energy balance
Straw
Physical pre-treatment
Process parameters

A B S T R A C T

Anaerobic digestion (AD) is a useful method for producing renewable energy/biofuel. Today, biogas production uses a large amount of energy crops (EC), with the effect of increasing AD costs and creating conflict between food/feed vs. energy use. A partial solution to this might be the substitution of EC with agricultural wastes, e.g. straw. Straw and corn stover are widely available in the world and approximately 1600 million Mg year^{-1} of these substrates are available. Straw can be useful used for biogas production but its characteristics limit its performance so that sometimes the energetic balance can be negative.

In this review, the limits for the conversion of this substrate into biogas were investigated and solutions/proposals for getting higher straw biogas production performance are reported. In addition, energetic balances for untreated and pre-treated substrates are reported, giving indicative evaluations of the sustainability of straw and corn stover use for biogas production.

Contents

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http://dx.doi.org/10.1016/j.biotechadv.2016.09.004
0734-9750/

1. Introduction

The continuous increase in greenhouse gases and the need for energy security for the future have strengthened the interest of the world in the development and use of energy sources which are not petroleum based (Hamelinck et al., 2005; Sun and Cheng, 2002): this approach also addresses political decisions. For example, according to a European Council decision, the share of renewable energy in relation to total energy consumption should be equal to 20% by 2020 (https://ec.europa.eu/energy/en/topics/renewable-energy). Again, the percentage of biofuels in total fuel consumption should be 10% by 2020 (https://ec.europa.eu/energy/en/topics/renewable-energy). Equally in China, according to the Mid- and Long-Term Plan for Renewable Energy Development, renewable energy should account for 20% of total energy consumption by 2020 (Wang et al., 2009a, 2009b).

As consequence of such decisions, it will be essential to develop sustainable energy supply systems to meet the global demand for renewable energy and bio-fuels (Bauer et al., 2009). According to the United Nations, by 2050 up to 77% of the world's energy demands should be supplied from renewable sources (IPCC, 2011).

Biogas production represents a useful alternative to fossil-based energy production because it is an economic way of producing methane if compared to other technologies (Pohl et al., 2012) and it is more efficient in terms of energy produced vs. energy input than other technologies (Gerardi, 2003; Deublein and Steinhauser, 2010).

Energy crops represent one of the most used feedstocks to produce biogas, especially in Europe where they form a high percentage (30–40% of the total feed mix on wet weight basis) of the feeding mix in agricultural biogas plants (Riva et al., 2014). The wide use of energy crops is due to their high potential for producing biogas, allowing large size biogas plants to be proposed (>1 MW). On the other hand, energy crops account for about 30–35% of the total biogas production costs (Schievano et al., 2015) making their use non-sustainable without large benefits. A possible solution, reducing biogas costs and substituting for dedicated energy crops, thus saving biogas production potential, consists in the use of agricultural and/or municipal wastes. Particular attention has recently been paid to lignocellulose wastes (e.g. straw, corn stover) as they are particularly suitable for energy applications because of their availability on a large scale and at low cost (Ferreira et al., 2014). According to the research of Talebnia et al. (2010), lignocellulosic residues are the most abundant resource in the world for the production of bio-energy from anaerobic digestion. Agriculture, in particular, by producing many wastes, such as wheat, rice and corn straw, can play an important role in meeting the growing energy demand for anaerobic digestion feedstocks which are sustainable and low in cost (Chandra et al., 2012a, b,c).

Nowadays straw is used mainly for animal feed, as bedding for livestock or it is returned to the soil as a natural fertilizer. The rest of the straw is either not used or is burned, often in the open environment: this procedure is unsustainable from an environmental point of view. Therefore, only a small fraction of the straw produced in the world is used as biomass for biogas production (Chandra et al., 2012a,b,c) although its use for biogas production is dramatically increasing (Zeng et al., 2007a).

This review aims to bring together all the published research on the anaerobic digestion of straw, highlighting the strengths and weaknesses of this versatile substrate.

2. Straw availability and its characterization

2.1. Straw availability

Straw is produced in large quantities all over the world and about 1600 million Mg of straw, coming from the main agricultural crops (rice, wheat and corn) (Table 1), are annually produced (Zhong et al., 2011a,b).

Rice straw represents the main crop residue with a yearly production of 731×10^6 Mg; 90% of it is produced, above all, in the developing countries of East and South East Asia (Table 1), where it is used mainly as a feed for ruminants (Hameed and El-Khaiary, 2008). In China the production of rice straw was reported to be of 400×10^6 Mg in 2011 (Liu et al., 2011), that is about 50% of the rice straw produced in the world (Zeng et al., 2007a,b). According to Zhong et al. (2011a,b), the rice straw production in Asia amounted to 667.6×10^6 Mg, followed by America with 37.2×10^6 Mg, Africa with 20.9×10^6 Mg, Europe with 3.9×10^6 Mg and Oceania with 1.7×10^6 Mg.

The total world production of wheat straw amounts to $583{,}776 \times 10^6$ Mg, produced on 224×10^6 ha of cultivated land (NL Agency, 2013). Wheat straw is the main agricultural residue in Europe, with a total production of 140×10^6 Mg (Najafi et al., 2008), followed by America with 65×10^6 Mg, Asia with 16×10^6 Mg, Oceania with 10×10^6 Mg and Africa with 7×10^6 Mg. Wheat straw represents the second most abundant source of straw production in the world after rice straw (Horn et al., 2011; Talebnia et al., 2010).

Another source of straw or stover comes largely from the cultivation of corn (maize) and according to Zhong et al. (2011a,b) the world produces about 230×10^6 Mg of corn straw, mainly in America with 150×10^6 Mg and Asia with 45×10^6 Mg, followed by Europe with 31×10^6 Mg, Africa with 3.5×10^6 Mg and Oceania with 0.5×10^6 Mg.

However, straw could represent a good substrate for renewable energy production by anaerobic digestion (Deswarte et al., 2007; Pohl et al., 2012; Savkelova and Netrusov, 2012).

2.2. Chemical composition of straw and potential of biogas/biomethane production

Biogas production from straw depends on total solids content (TS) and on the composition of the organic matter composing the TS, i.e. cellulose, hemicellulose and lignin (Fernando et al., 2006). Lignin and hemicellulose are very resistant to anaerobic digestion (Xiao and Clarkson, 1997; Buffiere et al., 2006), and lignin in particular has been reported not to be degraded by anaerobic bacteria (Fernandes et al.,

Table 1
Straw availability in different countries and in the world.

Country	Straw availability in different countries and in the world (million tons)		
	Wheat	Rice	Corn
Asia	16[a]	668/618[b]	45[a]
Africa	7[a]	21/24.7[b]	3.5[a]
Europe	140[a]	3.9/4.1[b]	31[a]
America	65[a]	37/38.1[b]	150[a]
Oceania	10[a]	1.7[b]	0.5[a]
World	584[c]	731/685[b]	230[a]

[a] Najafi et al. (2008).
[c] NL Agency (2013)/Lim et al. (2012).
[b] Zhong et al. (2011a, b).