Chemical Engineering Journal 242 (2014) 254–259

Contents lists available at ScienceDirect

Chemical Engineering Journal

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

Biomethane potential of wheat straw: Influence of particle size, water impregnation and thermal hydrolysis

L.C. Ferreira [a], P.J. Nilsen [b], F. Fdz-Polanco [a], S.I. Pérez-Elvira [a,*]

[a] Department of Chemical Engineering and Environmental Technology, University of Valladolid, C/Dr. Mergelina, s/n, 47011 Valladolid, Spain
[b] Cambi AS, Skysstasjon 11ª, 1383 Asker, Norway

HIGHLIGHTS

- Assessment of the influence of thermal pretreatment on the anaerobic biodegradation of wheat straw.
- Optimum severity factor at 200 °C and 5 min (3.6 severity factor).
- Evaluation through BMP tests: 27% increase in methane productivity of steam exploded straw respect untreated straw.
- Cutting (3–5 cm) wheat straw showed to be better than milling (<1 mm).

ARTICLE INFO

Article history:
Received 25 April 2013
Received in revised form 1 August 2013
Accepted 12 August 2013
Available online 21 August 2013

Keywords:
Biochemical methane potential (BMP)
Particle size
Thermal hydrolysis pre-treatment
Wheat straw

ABSTRACT

The anaerobic digestion of organic wastes such as wheat straw represents a very interesting means of generating biogas while reducing the amount of waste to disposal. An enhancement in the hydrolysis limited digestion of straw can be achieved by optimizing operation and performing pre-treatments. In this study, the influence of particle size, water impregnation and thermal pre-treatment was investigated through biochemical methane potential tests (BMP). The maximum methane yield was obtained by heating the straw at 200 °C for 5 min followed by steam explosion, obtaining a 27% increase in methane productivity compared to non-treated straw (from 233 to 296 mL CH_4/gVS_{fed}). Cutting (3–5 cm) showed to be better than milling (<1 mm), and the impregnation of the straw with water helped to enhance BMP test results by 4–10% (supposed better mixing due to a 10 times reduction of solids concentration) but had no effect on thermal pre-treatment. On the contrary, the economic impact of milling and water addition on a thermal pre-treatment would be absolutely negative, increasing the operation cost necessary to reduce the size and to heat water, respectively.

1. Introduction

Wheat straw is the largest agricultural residue in Europe, and the second largest in the world, after rice straw [1,2]. Nowadays straw is either used as bedding material for livestock, applied to the soil as natural fertilizer or as biomass for energetic valorization. The search for renewable energy sources together with the concern on greenhouse gas emissions have increased the interest on lignocellulosic materials as a source of energy [3,4], which is particularly well suited for energy applications because of its large-scale availability, low cost and large production.

Anaerobic digestion of biomass is a more economical and environmentally beneficial way of biomass utilization compared to typical pathways to biodiesel or bioethanol [5].

However, the main obstacle impeding a more widespread application of straw as feedstock for anaerobic digestion is its low digestibility due to its refractory structure. Like other lignocellulosic biomass, wheat straw is a complex mixture of cellulose, hemicellulose and lignin. Bioconversion of wheat straw is favored because of its relatively low lignin content (15–20%) and high carbohydrate content (30–40 and 20–30%w/w cellulose and hemicellulose, respectively) [6]. Lignin surrounds and seals the cellulose structure while hemicellulose serves as a connection between both of them [7]. Therefore, hydrolysis is a slow and difficult process [8,9].

In order to improve the biodegradability of wheat straw, several methods have been investigated, such as mechanical size reduction from the organic particulate matter [10–13], or the introduction of a lysis pre-treatment, such as physico-chemical alkaline dilution [14], microwave pre-treatment [15,16] or thermal steam explosion [17–19]. This last option has proven to be very interesting, as it can be cost effective if a proper energy recovery is performed.

* Corresponding author. Tel.: +34 983184934; fax: +34 983423013.
E-mail address: sarape@iq.uva.es (S.I. Pérez-Elvira).

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http://dx.doi.org/10.1016/j.cej.2013.08.041

Hydrothermal steam explosion is performed without the addition of chemicals or oxygen, representing a potential solution for the pre-treatment of large quantities of lignocellulosic biomass [1,20].

In a steam explosion, biomass is heated and rapidly discharged to atmospheric pressure causing the explosion of the macromolecules, with the aim of upgrading the digestibility of lignocellulosic materials, by increasing porosity, removing lignin content and promote hemicellulose hydrolysis [18,21]. Although the successful use of steam explosion has been proved from the point of view of fermentation and ethanol production [1,22–25], the evaluation of the methane potential of steam-exploded straw is more recent [19,21,26], and open to many other wastes (corn stover, maizecrop waste, rice straw, herbaceous waste, manure, sewage sludge).

The studies performed specifically with wheat straw [1,18,21] have shown that the effect of the thermal pre-treatment depends on several factors, such as chip size, temperature and time. It is generally accepted that there is an optimum temperature in the range of 150–220 °C and 5–20 min, but care must be paid for too severe treatments due to the formation of inhibiting phenolic and heterocyclic compounds, such as furfural [10].

Chip size is a crucial parameter, as any sort of cutting or milling is necessary to avoid clogging and heat transfer problems during thermal treatment (overcooking the outside of large chips and formation of inhibitory compounds). However, a promising finding is that enzymatic hydrolysis is improved for larger biomass particle sizes [27], as milling is an energy intensive and expensive process. Regarding the anaerobic digestion process, the effect of particle size reduction on methane yield of agricultural wastes is contradictory: positive in some studies [12,28,29], while negative in others [30,31]. Therefore, the influence of particle size on wheat straw digestibility is still open to research.

The effect of water impregnation on thermal hydrolysis is a novel study in this paper. The impregnation of straw with acid or alkali has been successfully applied in enzymatic hydrolysis, while the influence of humidity on steam explosion effect is unexplored from the point of view of later methanization. From another point of view, dilution can be imperative to avoid overload or inhibition during the anaerobic digestion [32].

The aim of the present study is to evaluate the effect of particle size, dilution and thermal pre-treatment variables (temperature, time and water impregnation) on the biodegradability of wheat straw. For this purpose, batch anaerobic biodegradability tests were performed in order to check the biochemical methane potential (BMP) under different milling, washing and thermal hydrolysis conditions to determine individual and combined effects. Furthermore, a kinetic model has been used to obtain the specific rate constants to assess the relationship of the parameters evaluated.

2. Materials and methods

2.1. Raw material and experimental set-up

Wheat straw was grown in Valladolid (Spain), harvested in 2012 and characterized (Table 1). The original straw was ground (3–5 cm) or milled (<1 mm), according to the experimental set-up in Table 2.

Three series of experiments (A, B and C) were performed (Table 2) to cover the three scenarios to study: (A) influence of particle size and water dilution on wheat straw digestibility; (B) influence of steam explosion pre-treatment; and (C) influence of water impregnation time on thermal hydrolysis and digestion.

Table 1
Average characteristics of the original wheat straw.

	TS (g/kg)	VS (g/kg)	TCOD (g/kg)	TKN (g N/kg)	TOC (% weigh)	C/N
Series A–B	895 ± 11	821 ± 9	1075 ± 8	4.723	43.2 ± 0.3	92
Series C	924 ± 9	846 ± 5	1089 ± 6	4.578	43.4 ± 0.2	92

Table 2
Experimental set-up.

Series A			Series B				Series C			
Test	Particle size	Dilution	Test	T (°C)	t (min)	log R_0	Test	T (°C)	t (min)	Washing time (h)
A1	3–5 cm	No	B0	Untreated			C1			0
A2	3–5 cm	Yes	B1	170	15	3.2	C2	200	5	3
A3	<1 mm	No	B2	200	5	3.6	C3			12
A4	<1 mm	Yes	B3	220	1	3.5	C4			24

2.2. Particle size reduction and water impregnation

Based on bibliography (where references to particle sizes ranging from 0.2 mm to 10 cm can be found), two particle sizes were selected for series A: 3–5 cm pieces and powder <1 mm. In most of the references, the particle size influence is not assessed but established in the range of 1–5 cm [12,18,21,33].

The larger particle size was chopped with a cramp to get the desired interval 3–5 cm. A laboratory mill (Philips, HR7775) was used to grind the straw into a minor particle size (<1 mm) controlled with a sieve (CISA™). In the studies of series B and C only the major particle size were used.

Water addition in series A and C was performed by mixing the straw with water. In series A, the water was added when preparing the BMP tests (1:10 dilution), while in series C the straw was soaked for a desired washing time.

2.3. Thermal steam explosion pre-treatment unit plant

The pre-treatment was performed at the steam explosion pilot plant facility designed by Cambi AS and located at the wastewater treatment plant of Salamanca, Spain.

The steam explosion unit consists of a 30 L reactor vessel and a flash tank with a removable bucket to collect the pretreated material (Fig. 1). The steam is generated by a 25 kW electric steam boiler (200 L capacity) which can supply steam up to a maximum pressure of 34 bar (240 °C). Wheat straw is loaded into the reactor using a motorized ball valve (V1) at the top of the reactor. Steam is added to the reactor from the bottom, through an air-actuated valve (V2), heating the waste during the time established. The desired operation pressure (corresponding to a certain temperature) is set on the control panel unit, controlled automatically by the air-actuated valve (V2). For security reasons also a manual valve (V3) has to be opened to add steam to the pressure reactor. An air-actuated ball valve at the bottom of the vessel (V4) is responsible for the rapid pressure drop (explosion) and release of the pretreated biomass to the flash tank. The pretreated biomass is collected in a removable bucket at the bottom of the flash tank. Any steam that is not condensed leaves the unit via a carbon filter to remove smell.

In all the experiments, one kilogram of wheat straw was used. The reactor was fed to the unit and the reactor was pre-heated for 15 min before starting the experiments.

The effects of temperature and time were evaluated based on the severity factor ($\log R_0$, Eq. (1)), which is the common term used in steam pre-treatments [11]:

$$\log R_0 = \log\left(t \cdot \exp\left(\frac{T - 100}{14.75}\right)\right) \quad (1)$$

where t is the time (min) and T the temperature (°C).

Different pre-treatment conditions were tested varying temperature (ranging 170–220 °C) and time (ranging 1–15 min), based on