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Single-stage and two-stage anaerobic digestion of extruded lignocellulosic biomass

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HIGHLIGHTS

- Single-stage BMP and two-stage AD of TSE poplar wood hydrolysates were analyzed.
- Methanogens degraded lignin present in the solid stream while H_2-producers could not.
- Higher energy yields in the 2-stage AD process were observed after acidification.
- Improvement in feedstock COD removal efficiency in 2-stage system after acidification.
- Sequential $BioH_2$ and $BioCH_4$ production from extruded poplar wood was demonstrated.

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ABSTRACT

This study investigated in single-stage and two-stage batches, the anaerobic digestibility of hydrolysates obtained from poplar wood biomass pretreated using the twin screw extrusion (TSE) process. The TSE process produced two distinct sugar-rich streams i.e. the liquid and solid streams. The liquid streams showed significantly higher hydrogen production potential and rates, comparable methane production potential and yields, but higher methane production rates than the solid streams in the single-stage BMP tests. This study revealed that the two-stage process for separate acidogenic and methanogenic processes, maximized both COD removal efficiencies and energy recovery as well as enhanced the overall process efficiency. Energy yields of 11.6 $kJ/gCOD_{feedstock}$ and 9.8 $kJ/gCOD_{feedstock}$ were obtained from the liquid and solid streams respectively in the two-stage anaerobic digestion process compared with 8.7 $kJ/gCOD_{feedstock}$ and 8.3 $kJ/gCOD_{feedstock}$ obtained in the single stage BMP process which are a 33% and 18% increase respectively. Feedstock COD removal efficiency was enhanced in the second-stage BMP process after acidification by 16% and 14% for the liquid and solid streams respectively compared to the single-stage BMP process. This work demonstrated the overall potential of poplar wood hydrolysates for sequential hydrogen and methane production.

1. Introduction

Fossil fuels accounted for 81% of the total energy consumption in the U.S in 2013 while renewable energy accounted for only 8% and energy consumption is expected to grow at an average of 0.3% per year, from 2013 to 2040 [1]. The demand for developing sustainable energy has increased as a result of rapid population growth and depleting fossil fuel supplies. Biogas (e.g. methane and hydrogen) has received significant attention as an alternative and valuable energy source during the last decade and can be utilized for vehicle fuel, heat and electricity generation [2]. Lignocellulosic biomass found mostly in agricultural and food processing residues, municipal solid wastes, and forest residues, has a great potential for biogas production due to its high sugar content [3]. One of the major limitations in biogas production from lignocellulosic biomass is low biodegradability and production yield due to its complex crystalline structure and the presence of lignin thus necessitating pretreatment [4].

Among the various pretreatment processes available, extrusion is a simple, cheap, and well-established method which can be used as a physicochemical pretreatment for lignocellulosic biomass [5,6]. The extruder consists of intermeshing, co-rotating screws

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Nomenclature

APE	average percent error
B	cumulative methane yield at time t
B_o	ultimate methane yield at the end of the fermentation period
BHP	biohydrogen potential
BMP	biomethane potential
$C_{H_{2,i}}$ and $C_{H_{2,i-1}}$	fractions of gas in the headspace of the reactor in the present and preceding intervals respectively
COD	chemical oxygen demand
DM	dry matter
HMF	5-hydroxylmethyl furfural
k	methane production rate constant
P	biogas production potential
P (t)	cumulative biogas potential at time t
R_m	biogas production rate
S°	substrate
S°/X°	substrate-to-biomass ratio
SRT	solids retention time
TN	Total Nitrogen
TP	Total Phosphorus
TS	Total Solids
TSE	twin screw extruder/extrusion
TSS	Total Suspended Solids
V	volume
$V_{G,i}$ and $V_{h,i}$	total gas volumes accumulated between the preceding and present intervals and the total volume of reactor headspace in the present interval respectively
$V_{H_{2,i}}$ and $V_{H_{2,i-1}}$	cumulative gas volumes at the present (i) and preceding (i − 1) time intervals respectively
VFA	volatile fatty acids
VS	Volatile Solids
VSS	Volatile Suspended Solids
X	biomass
λ	lag phase

mounted on grooved shafts in a closed barrel [6,7]. This technology has proven to be viable and has great flexibility and adaptability with respect to scale up and process modifications [6].

While chemical and biological pretreatment methods change the physical and chemical properties of biomass, extrusion does not affect the chemical composition of biomass but changes its physical properties such as specific surface area, bulk density, and specific porosity [6,8,9]. Particle size and crystallinity of lignocellulosic biomass are reduced and the surface area of biomass and sugar availability are also increased by extrusion [8,10,11]. Extrusion pretreatment has also been known to improve biogas yields [12,13]. Compared to other physical pretreatment processes such as hydrothermal or steam explosion methods, the extruder is operated at a lower temperature which reduces energy consumption and operating costs and prevents lignin oxidation and carbohydrate degradation [5].

In addition, extrusion is applicable to a wide range of biomass including forest, agricultural and energy crops.

GreenField Specialty Alcohols (GFSA) pioneered a two-stage extrusion process which involves cooking the biomass in two steps [14,15]. The first is to liquefy, separate and recover the C5 sugars so that they will not “inhibit” the second step, which is conducted under more extreme conditions to expose the cellulose fraction and recover highly digestible C6 sugars. In the pretreatment process, extruder no. 1 conditions the incoming biomass by removing resins and toxins. Extruder no. 2 then completes the process by washing the cellulose and hemicellulose fractions, squeezing and separating the hemicellulose fraction from the cellulose fraction thus contributing to the pretreatment cooking of the biomass to make the cellulose fraction more digestible. The twin-screw extrusion process (TSE) is unique in that it recovers the most C5 and C6 sugars, in their cleanest forms, for optimal downstream utilization, without any chemical addition i.e. acids or bases which are commonly used in other cellulosic pretreatment technologies. Thus, GFSA TSE process achieves this through particle size changes using grinding elements, solubilisation of C5 through cooking at elevated temperatures and pressures, as well as separation and extraction of C5 through novel filtration elements.

There is limited information on biogas production from extruded biomass, since most researches have focused on bioethanol production. Karunanithy and Muthukumarappan [16] reported that fermentation results of feedstocks pretreated using the extrusion technology were limited. A good number of different biomasses have been reportedly treated using the extruder with limited studies on poplar wood (see Tables 1 and 2). Few studies reported the enhancement of methane production using extrusion pretreatment of other types of biomass and enhancement of hydrogen yields from poplar wood pretreated with other technologies, but there is no publication on hydrogen production from extruded poplar wood biomass. Using a twin-screw extruder, the degradability of organic matter was promoted and methane production yields from different biomasses (straw, grass, treated manure and deep litter) in batch tests were boosted from 9% to 28% after 90 days [13]. Chen et al. [17] compared the particle size reduction of rice straw by extrusion or milling pretreatment and observed that extrusion significantly reduced the particle size by around 25%. The aforementioned authors further reported that methane production of extruded rice straw was 1.5 and 2 times that of milled and untreated rice straw, respectively. Methane production from a mixture of rice straw silage, maize silage, and triticale silage in a continuously mixed digester increased by up to 16% and volatile solids (VS) degradation was accelerated by around 15% through extrusion [18]. Wahid et al. [19] reported that extrusion increased sugar availability from 21% to 42% for wheat straw and from 7% to 26% for deep litter and methane yields from 12% to 29% (wheat straw) and 4% to 11% (deep litter). Most recently, extrusion combined with sodium hydroxide pretreatment of rice straw was reported to enhance methane production by 54% and energy recovery increased from 39% to 60% [20].

A two-stage anaerobic digestion process which separates acidogenesis and methanogenesis, can increase energy recovery by the production of both hydrogen and methane and the enhancement of microbial stability in the system [21–24]. In order to recover biogas economically from various lignocellulosic biomass, several studies of two-stage anaerobic digestion have been carried out using thermomechanical pulp (TMP) (wastewater from thermomechanically treated eucalyptus wood) [25]; food waste [26]; olive pulp [27]; potato waste [28]; cheese whey [29]; molasses [30]; and thin stillage [23]. Vinas et al. [25] reported that methane yield from TMP wastewater in a two-stage anaerobic digestion was 0.34 L $CH_4/gCOD_{removed}$ with a 90% COD removal efficiency corresponding to a 12% and over 16% increase compared to a single-stage process respectively. Han et al. [26] optimized both acidogenic hydrogenesis and methanogenesis of the two-stage anaero-