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Enhancing methane production from rice straw by extrusion pretreatment

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HIGHLIGHTS

- Extrusion pretreatment had a significant effect on the particle size reduction.
- The physical priorities of rice straw were improved by extrusion pretreatment.
- The highest SMP obtained using the EPRS was 227.3 L/kg VS with an ISR of 0.4.
- The VMP obtained using the EPRS was 17.0 m^3/m^3 with an SLR of 90 kg/m^3.
- SEM analyses indicated that the cellulose of the EPRS was devillicated.

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ABSTRACT

Extrusion pretreatment was applied to enhance fermentative methane production from rice straw. The extrusion-pretreated rice straw (EPRS) showed significant particle size reduction, physical properties improvement and volume expansion, as compared to the milling-pretreatment rice straw (MPRS) and unpretreated rice straw (UPRS). The anaerobic digestion of EPRS, MPRS and UPRS with different inoculum-to-substrate ratios (ISRs) and solid loading rates (SLRs) was investigated. The highest specific methane production (SMP) of the EPRS was 227.3 L/g VS with an ISR of 0.4 and SLR of 50 kg/m^3, which was 32.5% and 72.2% greater than that of the MPRS and UPRS at the corresponding ISR and SLR, respectively. Furthermore, the volumetric methane production (VMP) increased with increasing SLR. The highest VMP (17.0 m^3/m^3) of the EPRS was obtained with an SLR of 90 kg/m^3, which was 1.5 times that of the MPRS. In addition, the EPRS had significantly shorter technical digestion time and higher cellulose and hemicellulose degradation efficiencies, which was due to the smaller particle size and larger specific surface area of the EPRS, thus contributing to the enhancement of methane production. The SEM analyses further demonstrated that the cellulose of the rice straw was devillicated after extrusion pretreatment, which was in agreement with the higher cellulose and hemicellulose degradation efficiencies of the EPRS.

1. Introduction

In China, the 2011 energy consumption was 3.48 Gt standard coals, of which coal, petroleum and natural gas was accounted for 68.4%, 18.6% and 5.0%, respectively [1]. The excessive consumption of fossil fuels brings about a series of problems, such as the increasing greenhouse gas concentration in the atmosphere, the worsening of the global climate and the decreasing supply of fossil fuels. Therefore, the exploration of new, sustainable and renewable energy to replace exhaustible fossil fuels is urgent [2]. Lignocellulosic biomass (agro-residues, forest-residues, etc.) is considered a primary candidate for producing bio-energy due to its abundant renewable resources [3]. Crop straws (corn stover, wheat straw and rice straw) are the major components of agro-residues in China [4]. The annual output of crop straws in China is more than 0.7 billion tons and about 0.5 billion tons (70.6%) are comprehensively utilized, among which about 0.22 billion tons (31.9%) are used for animal feed, 0.11 billion tons (15.6%) for fertilizer plowing into field, 0.02 billion tons (2.6%) for culture medium of edible fungi, 0.02 billion tons (2.6%) for papermaking and artificial board, and 0.12 billion tons (17.8%) for fuel (cooking, house heating, biogas and straw syngas) [5]. Large amounts of unused crop straws are burnt in the open fields, which both has a deleterious effect on the local air quality and wastes biomass resources [4]. Rice straw is one of the most abundant crop straws in central and southern China with an annual yield of nearly 0.3 billion tons [6]. As a typical lignocellulosic biomass, rice straw is mainly composed of cellulose (appr. 34 wt%)

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Nomenclature

AD	anaerobic digestion
C/N	carbon to nitrogen ratio
$C_{b,i}$	the methane content of the blank control, %
$C_{e,i}$	the methane content of the experimental group, %
$Cellulose_{de}$	the degradation efficiency of cellulose, %
$Cellulose_{rs}$	the cellulose content of the rice straw, %
CH_4	methane
CMP	cumulative methane production
CO_2	carbon dioxide
EPRS	extrusion pretreated rice straw
$Hemicellulose_{de}$	the degradation efficiency of hemicellulose, %
$Hemicellulose_{rs}$	the hemicellulose content of the rice straw, %
ISR	inoculum to substrate ratio, VS/VS
MMP	maximal methane production
MPRS	milling pretreated rice straw
SEM	scanning electron microscopy
SLR	solid loading rate, kg/m^3
SMP	specific methane production, L/kg VS
T_{80}	technical digestion time, d
TC	total carbon
TN	total nitrogen
TS	total solid
TS_b	the TS content of the digested residues of the blank control, %
TS_{de}	the degradation efficiency of TS, %
TS_{rs}	the TS content of the rice straw, %
UPRS	unpretreated rice straw
V/V	volume to volume
$V_{b,i}$	the biogas volume of the blank control, ml
$V_{e,i}$	the biogas volume of the experimental group, ml
V_w	working volume, ml
VMP	volumetric methane production, m^3/m^3
VS	volatile solid
VS_b	the VS content of the digested residues of the blank control, %
VS_{de}	the degradation efficiency of VS, %
VS_{rs}	the VS content of the rice straw, %
W_b	the weight of the digested residues of the blank control, g
W_{re}	the weight of the digested residues of the experimental group, g
WHC	water-holding capacity, g/g

making up by the same anhydroglucose units, hemicellulose (appr. 28 wt%) consisting of different polymers like pentoses and hexoses, and lignin (appr. 10 wt%) forming a three-dimensional network by phenylpropane units [7,8]. It is an organic-rich material and can be used as potential feedstock for bioenergy [7,9].

Recently, the biological production of methane, hydrogen, ethanol and other biofuels from straw has drawn much attention [9–13]. Methane is the main component of biogas, which is produced using anaerobic digestion (AD) by a variety of microorganisms to decompose organic matter under oxygen-free conditions [14]. AD usually involves four stages (hydrolysis, acidogenesis, acetogenesis and methanogenesis) [15]. Among the four stages, hydrolysis is usually considered the rate-limiting step, which affecting the conversion efficiency of straw. Many studies focused on accelerating straw hydrolysis and increasing the methane yield by physical, chemical, biological or physicochemical pretreatment methods [16–20]. Each pretreatment method has advantages and disadvantages, and there is no "ideal" method [8]. Physical pretreatment can reduce the particle size and increase the surface area and pore-size by releasing intercellular components which increases the hemicellulose hydrolysis and further accelerates cellulose hydrolysis, but it is higher energy-demanding [8]. Hence, physical pretreatment like milling is less attractive in practical application. Chemical pretreatment with acid, alkali or aqueous ammonia is simple, quick, and effective at changing the chemical compositions of the biomass and increasing surface accessibility for anaerobic microorganisms by decreasing cellulose crystallinity [21–23], but it increases the cost and causes secondary pollution [24]. Even worse, inhibitors or toxic substances such as furfural, hydroxymethylfurfural, levulinic and phenolic compounds are always produced in the chemical pretreatment [8,25]. Biological pretreatment using microorganisms (white, brown and soft rot-fungi) is energy-saving and uses mild operation conditions, but it requires a long residence time to degrade the lignin; additionally, it is difficult for large-scale applications [8,18,24].

However, as particle sizes larger than 2 mm limit the heat and mass transfer during hydrolysis [26], particle size reduction is necessary for straw to produce methane. In addition, particle size reduction can increase the specific surface area and bulk density and decrease the volume of straw. The biomass size reduction equipment include a shredder, ball mill, hammer mill, knife mill, disc mill, two roll mill, colloid mill and extruder [26]. In addition to size reduction, the extruder can provide a continuous thermo-mechanical treatment, which is widely employed as a mechanical pretreatment method for lignocellulosic biomass ethanol production, pulping and papermaking [27,28]. Recently, the extruder, as a novel and promising machine, has been used for biomass conversion to methane [29,30]. During the extrusion pretreatment process, the biomass is subjected to shearing, heating and mixing, disrupting the lignocellulose structure and resulting in the defibrillation, fibrillation and shortening of the fibers [26]. The physical and chemical change after extrusion pretreatment makes the cellulose and hemicellulose accessible to enzymatic attack and increases the methane production [26]. Hjorth et al. (2011) investigated the extrusion pretreatment of five agricultural biomass types prior to producing methane and found that the methane production increased by 9–28% after 90 days and resulted in energy surpluses of 6–68% after subtracting the energy consumed by the extruder [29]. Other pretreatments like milling, thermal, acid, alkaline, hydrothermal and white-rot fungi pretreatment have been intensively reported [10,16,18,19,22]. However, there is little information about the effect of the extrusion pretreatment of rice straw on methane production.

Therefore, the major objective of this study was to investigate the influence of extrusion pretreatment on methane production from rice straw, a typical lignocellulosic biomass. Furthermore, the physical properties, such as particle size distribution, bulk density, water-holding capacity, specific porosity and specific surface area, were determined after extrusion pretreatment, and the chemical composition was also analyzed. In addition, the mechanism of the extrusion pretreatment for significantly elevated methane production from rice straw was explored.

2. Methods

2.1. Feedstock and inoculum

The rice straw used in this study was collected from Yancheng city, Jiangsu province, China, and dried at room temperature. The dried rice straw was then cut into 50-mm sections by a paper