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Research paper

Biogas production from reed biomass: Effect of pretreatment using different steam explosion conditions

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ABSTRACT

Biogas production often competes with food and feed production for the raw materials and cropland required for cultivation. Common reed offers an alternative source of biomass for biogas production, alleviating this conflict. Effective microbiological conversion of this type of lignocellulosic biomass requires a pretreatment process. This study aims to determine the specific methane yields of steam-exploded reed as well as to identify how pretreatment conditions influence its physico-chemical characteristics. For this purpose, reed was pretreated with steam explosion at severity factors ranging from 2.47 to 4.83. The effects on methane yields were analyzed in batch experiments. Scanning electron microscopy (SEM) images were captured and detailed chemical analyses of the substrates carried out. Results show that the digestibility of reed biomass improved remarkably after pretreatment. Compared to the untreated sample, steam explosion increased the specific methane yield up to 89% after pretreatment at 200 °C for 15 min. However, methane yield decreased under harsher conditions, which may be due to the formation of degradation compounds during the pretreatment.

1. Introduction

Using anaerobic digestion (AD) to produce renewable energy has increased in popularity over the last decade. The technology is economical, eco-friendly, and can produce renewable energy and valuable fertilizers from a wide range of organic materials [1,2]. Nevertheless, the utilization of some substrates for AD can compete directly with food and feed production [3]. In order to mitigate this conflict, sustainable strategies are being developed to include agro-industrial and municipal residues, as well as alternative biomass sources (such as aquatic vegetation) that do not require arable fields.

Common reed (*Phragmites australis*) is a highly productive grass, frequently found in marshes and in the littoral zone of lakes, rivers and estuaries [4]. Under certain circumstances, common reed can be considered tremendously invasive, in some cases becoming a major ecological concern [5]. Measures to control or mitigate reed populations can provide local communities with significant amounts of biomass for sustainable biofuel production while also reducing water eutrophication [6].

Common reed is a lignocellulosic biomass composed mainly of the polymer groups cellulose, hemicellulose and lignin. These polymers form the lignocellulosic complex, which creates a protective barrier that hinders microorganisms from accessing carbohydrates [7,8]. The hydrolysis of cellulose and hemicellulose into fermentable sugars is an essential step in the AD process. The application of a pretreatment method to alter the structure of lignocellulosic biomass is required in order to improve hydrolysis rates [8]. Efficient pretreatment methods should preserve available

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sugars, avoid the formation of inhibitors, and also prove economical [9]. A large variety of pretreatments have been studied for biomass conversion and can be roughly classified as physical, chemical, biological or a combination of all three [9,10].

Steam explosion, a physico-chemical pretreatment, is considered to be one of the most cost-effective pretreatment methods for breaking the lignocellulosic bonds of biomass [11]. This pretreatment method entails heating biomass to a high temperature under high pressure and, after a specified retention time, abruptly decreasing the pressure [12,13]. Steam explosion disrupts the lignocellulosic complex, solubilizes the hemicellulose into individual sugars and oligomers, and substantially increases microbial enzymatic hydrolysis [14]. Moreover, it opens up the biomass particle structure, thereby reducing particle size and increasing pore volume [12,15]. Steam explosion without the utilization of external catalysts has proven to be an efficient pretreatment method for ethanol and biogas production from a wide variety of lignocellulosic substrates, including agricultural residues [16–19], hardwoods [20,21], byproducts from ethanol production [22], food processing waste [23,24] wastewater sludge [25], municipal waste [26] and manure [27]. Nevertheless, steam explosion can result in degradation products such as furan derivatives, which may have an inhibitory effect on the microorganisms involved in the AD process [28,29]. Therefore, to achieve efficient AD processes, optimal steam explosion conditions must be identified for each specific type of biomass.

Integrating aquatic perennial grass into biogas systems as a sustainable feedstock can have a variety of advantages. When dry-harvested in winter, reed biomass can be stored over a long period of time, ensuring a high degree of operational flexibility. In addition, harvesting can help to control common reed populations and remove nutrients from bodies of water. Assessing the suitability and profitability of utilizing common reed for biogas production requires various analyses to be carried out. Determining the biomethane potential in batch tests is one such analysis. Although some studies have examined the methane potential of aquatic perennial grasses, such as giant reed (*Arundo donax L.*) [30,31] and reed canary grass (Phalaris arundinacea *L.*) [32,33], research on the utilization of common reed for AD remains sparse. The only study on the anaerobic degradability of common reed found in the literature was performed by Jagadabhi et al. [34], which analyzed the methane production of maritime common reed harvested from the Baltic Sea (Finland). To the best of our knowledge, no study has been conducted on the methane potential of common reed grown in fresh water. In order to fill this gap in the literature, this study determined the specific methane yield of untreated freshwater common reed, as well as the effect of steam explosion on its specific methane yield. In addition, the impact of pretreatment on the morphology and physico-chemical characteristics of the biomass was analyzed to provide a deeper understanding of the effect of steam explosion on common reed. This information can be used to determine optimum pretreatment conditions.

2. Materials and methods

2.1. Raw material and steam explosion pretreatment

The reed biomass used in this study (*Phragmites australis* subsp. *australis*) was harvested in December 2010 at Lake Neusiedl in Austria (47°50′N 16°43′E). Neusiedl is a shallow lake with an average water depth of 1.2 m. It is considered a meso-eutrophic water body [35,36], characterized by a large belt (estimated area of 180 km^2) of common reed [35]. The lake's harvestable yield of common reed is approximately 6 t DM ha^{-1} (calculated based on Köbbing et al., [37]). Reed harvesting for this study took place when the lake was frozen. Reed was cut at approximately 1.3 m above the root collar. After collection, the reed was dried in piles at the harvest site and subsequently shredded to reduce size to less than 20 cm. The shredded biomass was packed and vacuum-stored at 4 °C until the pretreatment could be performed.

The harvested reed was pretreated in the steam explosion unit located at the Norwegian University of Life Sciences (NMBU) in Ås (Norway), as described by Horn et al. [13]. The unit consisted of a 20 dm^3 pressure vessel and a flash tank with a removable bucket to collect the pretreated material. An electric steam boiler (Parat, Flekkefjord, Norway) supplied steam to the reactor at pressures reaching up to 3.4 MPa. Air was removed from the reactor before each pretreatment by directly injecting steam until saturation was reached. Temperatures were indirectly controlled by regulating the pressure in the reactor using a manometer connected to an automatic valve. The pretreatment process was carried out at temperatures ranging from 160 to 220 °C, using intervals of 20 °C. Each temperature was maintained for 5, 10, 15 or 20 min. After each steam explosion pretreatment, the unit was cleaned by running three 'steam-only' steam explosions and subsequently flushing the flash tank and bucket with tap water. All pretreated samples were stored in vacuum bags at 4 °C until further biogas and analytical tests could be performed.

The pretreatment variables of temperature and time can be combined into a single reaction ordinate (R_O) commonly referred to as the severity factor (SF) [38]. The SF, calculated as (log R_O), is defined in Eq. (1).

$$\log(R_O) = \log(t * \exp((T - 100)/14.75)) \quad (1)$$

where t is the reaction time in minutes and T is the treatment temperature in degrees Centigrade and 14.75 is the activation energy value under conditions where the process kinetics are first order, following the Arrhenius law.

2.2. Imaging with scanning electron microscopy (SEM)

In order to document the disruptive effect of steam explosion on the pretreated samples, scanning electron microscopy (SEM) was carried out at the University of Natural Resources and Life Sciences, Vienna. First, samples were sputtered with a very thin layer of gold to guarantee their electrical conductivity. A gold film of approximately 10 nm thickness was applied using a Scancoat Six SEM sputter coater (Edwards, UK). The scanning electron microscope FEI Quanta 250 FEG (FEI Inc., USA) operates with a field emission gun and is additionally equipped with an energy-dispersive X-ray spectrometer (EDS) EDAX Apollo X-SDD (Edax, USA). Observations were performed at a total magnification of 100× and 500×.

2.3. Chemical analysis

The dry matter (DM) content of the biomass was determined by drying samples at 105 °C until a constant weight could be measured. Ash and volatile solids (VS) content was determined after dry oxidation at 550 °C in a muffle furnace according to Sluiter et al., [39]. Cellulose, hemicellulose and lignin were determined in duplicates as described in Bauer et al. [28], and based on Van Soest and Wine [40]. The contents of neutral detergent fiber (NDF), acid detergent fiber (ADF) and acid detergent lignin (ADL) were also determined according to this method. The hemicellulose content was calculated as the difference between NDF and ADF and the cellulose as the difference between ADF and ADL.

The elemental analysis of the samples was carried out at the Microanalytical Laboratory of the University of Vienna. The elemental analyzer EA 1108 CHNS-O (Carlo Erba, Italy) was used for