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The effect of microwave pretreatment on biogas production from agricultural straws

Zehra Sapci *

Department of Mathematical Science and Technology, Norwegian University of Life Sciences, IMT Building, UMB, Ås 1432, Norway

HIGHLIGHTS

- ▶ Barley, spring wheat, winter wheat and oat straw were examined.
- ▶ Microwave pretreatment were performed at 200 and 300 °C.
- ▶ The biogas production performance was investigated.
- ▶ Specific methane yields were not improved by microwave irradiation.
- ▶ Conversion yield and cumulative biogas production have inverse relations.

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ABSTRACT

Biogas production from microwave-pretreated agricultural residual straws that are used as feedstock was investigated in a laboratory batch study. Barley, spring wheat, winter wheat and oat straw were examined. To investigate the effect of changing the physicochemical structure of the straws on biogas production, the pretreatment processes were applied to two sample groups. The first group contained milled straw and the second group comprised milled wet straw that was prepared by the addition of deionized water. Both groups were subjected to microwave irradiation until oven temperatures of 200 or 300 °C were attained. Sixty-six identical batch anaerobic reactors were run under mesophilic conditions for 60 days. Preliminary test results showed that the microwave pretreatment of the different straws did not improve their anaerobic digestion. An increase in the treatment temperature led to lower biogas production levels. An inverse relationship between the thermal conversion yield and cumulative biogas production was observed.

1. Introduction

Studies on the conversion of whole crop cereals and their residues into energy and valuable chemicals show very promising future applications. In recent years, the anaerobic digestion process has been used to obtain energy from lignocellulosic residues in co-digestion, because it provides a higher content of carbon for the digestion. The different types of lignocellulosic biomass vary in the percentages of the major constituents, i.e., cellulose, hemicelluloses, lignin, organic extractives and inorganic minerals, depending on their origin and species (Mohan et al., 2006). The cellulose chains are packed by hydrogen bonding in "elementary microfibrils." These fibrils are attached to each other by hemicelluloses and by other polymers such as pectin and are covered by lignin. The microfibrils often associate as bundles or macrofibrils. These strong chains form a crystalline ribbon that makes cellulose resistant to biological treatments by making it less available for microbial and enzymatic hydrolysis. Consequently, the most rate-limiting stage of biomass degradation is reported to be the hydrolysis stage of the digestion process. Similarly, lignocellulosic biomass must be pretreated to make it less resistant and more exposed for improved hydrolysis efficiency (Zhu et al., 2010). Pretreatment is a process that makes biomass more hydrolysable than it is in its hydrolysis-resistant native state. There are many pretreatments technologies, such as thermal, biochemical, mechanical and enzymatic treatments (Estevez et al., 2012; Jackowiak et al., 2011). To observe the pretreatment effects, anaerobic batch experiments are employed to determine the biochemical methane potential of the pretreated biomass (Jackowiak et al., 2011; Zhu et al., 2010).

In thermal pretreatment, heat is either transferred into the material through convection, conduction or radiation using conventional heating, or it is delivered directly into the material through molecular interaction with an electromagnetic field using microwave energy. The electromagnetic energy of the microwave radiation is converted to thermal energy. The microwave technique has many potential advantages, as it penetrates materials, deposits energy and generates heat throughout the volume of the material.

* Tel.: +47 64965496; fax: +47 64965401.
E-mail address: zehra.sapci@umb.no

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The transfer of energy enables the achievement of rapid and uniform heating of materials. The use of microwave energy reduces the heating period of the material (Thostenson and Chou, 1999). The potential advantages include not only uniform heating of the material and reduced processing time but also increased energy efficiency, rapid and controlled heating and exceptional control over the heating process (Nour et al., 2010; Robinson et al., 2010; Huang et al., 2008).

The microwave irradiation could lead to one or more changes in the features of the cellulosic biomass, including increased specific surface area, decreased polymerization and crystallinity of the cellulose, hydrolysis of the solubilized oligomers of hemicellulose and partial depolymerization of lignin (Odhner et al., 2012). It can make the substrate more accessible to enzymes due to increased availability of contact surfaces and decreased crystalline structure. Therefore, thermal pretreatment using microwave radiation may be a good method for biomass pretreatment, as it disrupts the complex and rigid structure of the biomass that makes it resistant to mechanical stress and enzymatic attack. Although the irradiation has been widely applied to pyrolysis processes as an established and promising method for producing syngas, pyroloictic liquids (tar and pyroligneous acids) and chars (Robinson et al., 2010), only a few of studies have been devoted specifically to the study of microwave irradiation (under atmospheric condition) for the pretreatment of biomass (Jackowiak et al., 2011). Thermal pretreatment by microwave irradiation may be a good candidate for the pretreatment of biomass because it disrupts the complex lignocellulosic structure. Hence, the applicability of microwave irradiation needs to be evaluated for the pretreatment of lignocellulosic material.

A study emphasized that during the microwave irradiation of biomass, the moisture is removed as the temperature rose from ambient temperature to 100 °C (De Wild et al., 2011). Degradation of the biomass to decompose its components by slow pyrolysis has demonstrated that hemicellulose is lost at temperatures ranging from 130 to 194 °C (Mohan et al., 2006). Another pyrolysis study showed that hemicelluloses, cellulose and lignin collapse at temperatures ranging from 197 to 257 °C, 237 to 347 °C and 277 to 497 °C, respectively (Demirbas, 2004). Large amounts of hemicelluloses and cellulose are destroyed when biomass is torrefied at 290 °C (Medic et al., 2012; Chen and Kuo, 2011).

The objective of this study was to determine the effects of microwave pretreatment on the digestibility of Norwegian agricultural residual materials under anaerobic mesophilic conditions. Four different types of agricultural straws, winter wheat (WW), spring wheat (SW), oat straw (OS) and barley straw (B), were selected and the biogas potential was investigated. Two wheat straws, WW and SW, were investigated separately because of their different characteristics. SW has no vernalization requirement and develops reproductively in response to increasing temperature and photoperiod, while WW development is based on a vernalization requirement rather than the season when they are usually sown (Loomis and Connor, 1998).

2. Methods

2.1. Biomass collection

WW, SW, OS and B were collected from locations near the around the Norwegian Agricultural University of Life Sciences campus in Aas, Norway. After the harvest period (fall of 2010), all of the straw materials were baled in a plastic bag in the field. Thermal conversion requires the feedstock to be dried, which is an energy-intensive process (Wang et al., 2008). This process is energy intensive because the bales were not opened until their arrival at the laboratory where the experimental equipment was available.

2.2. Drying and milling processes

Before starting the experiments, the materials were stored at room temperature to minimize temperature differences and to remove the undesired moisture content. To obtain small particle sizes of the straws, the air-dried straws were milled (2000 rpm, 3 min) using a Retsch Knife Mill (GRINDOMIX GM 300 – Germany) and were then referred to as milled straw (MS). Each type of MS was manually mixed in a large plastic container for approximately 10 min to obtain a uniform environment in the feeding material. The homogenized MS was then stored at room temperature until further use.

The particle size distributions of the four types of milled straws are given in Fig. 1. Table 1 indicates the results of their proximate and physico-chemical properties.

2.3. Microwave pretreatment process

A microwave experiment was conducted in a laboratory-scale CEM Microwave Max asphalt oven (15 Amps, 50 Hz for 220–240 V). The oven's original thermocouple sensor was positioned inside the microwave after it was calibrated using another sensor (TENMA 72-7712 CE dual-input digital thermometer, type K thermocouple probes); thereafter, the temperature nearby the reactor was adapted to express the relative thermal effect of microwave power in accordance with the work of Huang et al. (2008). The average heating rate was 5 °C min^{-1}. Microwave pretreatment of MS (100 g) was performed at 200 and 300 °C with a hold time of 15 min. The procedures were not run in the complete absence of air, which distinguishes them from the procedure used for torrefaction (mild-pyrolysis) (Medic et al., 2012). After the microwave pretreatment process, the solid residues were allowed to cool to approximately 100 °C and placed in desiccators for around 3 h. The solid residues were weighed at room temperature (Huang et al., 2008). The final weight of the sample was determined to calculate the solid yield (SY) (%) according to the pyrolysis process, even though the process used differed from pyrolysis because it was performed in the presence of air. To determine the amount of organic matter (OM) (g), Eq. (1) was used and the SY was calculated according to Eq. (2). Depending on the SY, the pyrolysis conversion (PC) ratio was obtained using Eq. (3):

$$\mathrm{OM(g)} = \mathrm{AM(g)} - [(\mathrm{PA}(\%) + \mathrm{PM}(\%))/100] \cdot \mathrm{AM(g)}] \tag{1}$$

$$\mathrm{SY}(\%) = [[\mathrm{CP(g)} - (\mathrm{AM(g)} \cdot \mathrm{PA}(\%)/100)]/[\mathrm{AM(g)} - (\mathrm{AM(g)} \cdot \mathrm{PA}(\%)/100)]] \cdot 100 \tag{2}$$

$$\mathrm{PC}(\%) = 100 - \mathrm{SY}(\%) \tag{3}$$

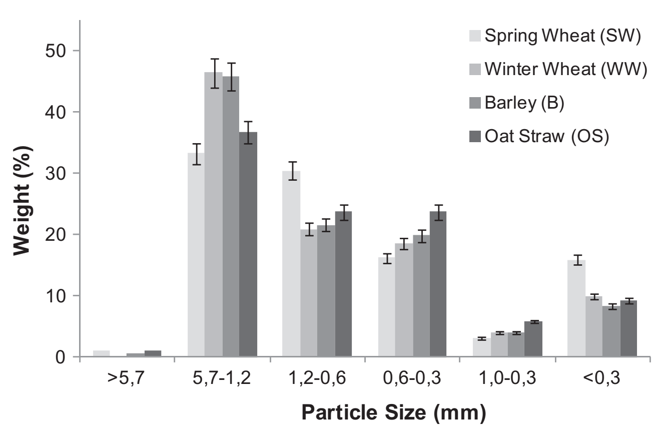

Fig. 1. Particle size distribution of the milled straws (MSs).