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Anaerobic batch conversion of pine wood torrefaction condensate

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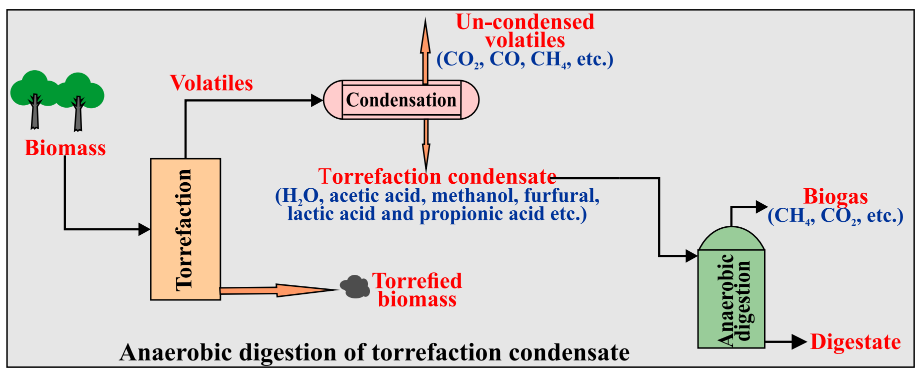
HIGHLIGHTS

- Torrefaction condensate is a good substrate for anaerobic digestion.
- Torrefaction temperature affects both condensate composition and the methane yield.
- Anaerobic digestion under mesophilic conditions yielded better methane yield.
- Under optimized conditions, a maximum methane yield of 492 mL/g VS was observed.

GRAPHICAL ABSTRACT



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ABSTRACT

Organic compound rich torrefaction condensate, owing to their high water content and acidic nature, have yet to be exploited for practical application. In this study, microbial conversion of torrefaction condensate from pine wood through anaerobic batch digestion (AD) to produce methane was evaluated. Torrefaction condensate exhibited high methane potentials in the range of 430–492 mL/g volatile solids (VS) and 430–460 mL/g VS under mesophilic and thermophilic conditions, respectively. Owing to the changes in the composition, the methane yields differed with the torrefaction condensates produced at different temperatures (225, 275 and 300 °C), with a maximum of 492 ± 18 mL/g VS with the condensate produced at 300 °C under mesophilic condition. The cyclic batch AD experiments showed that 0.1 $VS_{substrate}$:$VS_{inoculum}$ is optimum, whereas the higher substrate loading (0.2–0.5) resulted in a reversible inhibition of the methane production. The results suggest that torrefaction condensate could be practically valorized through AD.

1. Introduction

The European Union has set the political targets of increasing the primary energy consumption from renewable resources up to 20% by 2020 and 27% by 2030 (Thrän et al., 2016). Co-firing biomass in existing coal power plants is being considered as one option to achieve these renewable energy targets. In order to enhance the fuel properties, biomass needs to be pre-treated before being fed into the existing coal-firing power plants. Torrefaction is one such pre-treatment process, which enhances fuel properties of the biomass by increasing the energy density and hydrophobicity and by reducing the moisture content and the required grinding energy (Doddapaneni et al., 2016). Torrefaction is carried out in the range of 200–300 °C. The degradation mainly occurs between 275–300 °C and the product distribution also significantly varies in this temperature range. The thermal devolatilization of biomass proceeds with

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strong exothermic reactions in the range of 270–290 °C (Fagernas et al., 2015). According to Thrän et al. (2016), the quality of the torrefied biomass depends on its degree of torrefaction and the degree of torrefaction depends on the temperature and the residence time. To maximize the solid product yield, generally torrefaction is carried-out at low temperature and long residence time in commercial torrefaction equipment.

Torrefied biomass is being considered for a variety of industrial processes such as pyrolysis, gasification, cement kilns, as a substitute for coke in the steel industry and, in addition to all of this, it can be used as a fuel for co-firing in coal-fired power plants (Thrän et al., 2016). In spite of these advantages, still torrefaction needs to be proved for its technical and economic feasibility (Koppejan et al., 2012). As listed by Koppejan et al. (2012), several issues in the development of the torrefaction technologies, for example, energy integration, volatile gases handling and applicability of multi feedstock are need to be addressed. To improve the technical and economic feasibility, the energy integration within the process must be optimized and at the same time additional value should be generated through the byproducts like the torrefaction condensate.

Torrefaction condensate produced from different feedstock and at different operating conditions have been characterized in the past e.g. (Liaw et al., 2015; Tumuluru et al., 2011b, and Fagernas et al., 2015). The majority of the compounds (i.e. acids, alcohols, aldehydes, furans and phenols) at the concentration as present in the torrefaction condensate are water-soluble (Fagernas et al., 2015). Among the water soluble compounds, acetic acid, methanol, furfural, formaldehyde, hydroxymethylfurfural and phenol contributes to 80–90 wt.% of the total organic fraction of the condensate (Fagernas et al., 2015).

In general, the torrefaction volatiles are combusted to meet the heat energy requirements within the process (both drying and torrefaction units), and according to Liaw et al. (2015), it has very little effect on the process integration and overall economic viability of the process. In spite of having several valuable chemicals, owing to their complex composition, the torrefaction condensate has not yet been studied for its actual potential (Fagernas et al., 2015).

Biochemical conversion of torrefaction condensate into useful products could be one potential option for its valorization. Anaerobic digestion (AD) is a biochemical process of converting complex organic material into methane and carbon dioxide using a consortium of microorganism. AD comprises of different stages, initially the complex organic material is converted into volatile fatty acids (VFA) through hydrolysis and acidogenesis. In the later stage VFAs are further converted to acetic acid, CO_2, H_2, NH+ etc. through acetogenesis. In the final stage, the intermediate products are further converted into CH_4 and CO_2 by methanogens (Fabbri and Torri, 2016). As torrefaction condensate has high water content (50–85%), and acetic acid (5–15%) and other organic acids like formic acid and lactic acid (Tumuluru et al., 2011a and Liaw et al., 2015), which are readily anaerobically converted, torrefaction condensate could be an optimum feedstock for AD process and it is expected that the methane yields could be higher in comparison with other complex substrates. However, at the same time the inhibitory effects on AD by the presence of compounds such as furfural and phenolics in the torrefaction condensate should also be considered (Liaw et al., 2015).

On the other hand, the earlier studies on bio-oils are mainly focused on the biochemical conversion of pyrolysis oil. Fabbri and Torri (2016), studied linking the pyrolysis with AD and suggested that AD of pyrolysis volatile fractions is one of the best approaches to increase the energy recovery but there is a knowledge gap in these kinds of process integration in terms of multidisciplinary interface. Hübner and Mumme (2015), studied the AD of the aqueous liquors from the pyrolysis of digestate obtained from on-farm biogas plant and reported that volatile organic compounds (VOCs) except cresols present in the pyrolysis aqueous phase where degraded below the detection limit. Lian et al. (2012), studied the yeast fermentation of carboxylic acids separated from pyrolysis aqueous phase and proved its feasibility for lipid production through oleaginous yeast. In their study, Lian et al. (2013) reported that, the fermentation of levoglucosan obtained from the pyrolysis oil is one possible approach for the biofuel production. Torri and Fabbri (2014) studied the AD of aqueous pyrolysis liquid and reported that addition of bio-char increased the methane yield by reducing the inhibition level of the pyrolysis oil to the microorganism.

Even though there is a significant difference in the composition between torrefaction condensate and pyrolysis oil, the earlier knowledge on the biochemical conversion of pyrolysis oil could be useful while working with torrefaction condensate. At the same time, to our knowledge there is only one study reported on the AD of torrefaction condensate. Liaw et al. (2015), studied the mesophilic batch AD of the torrefaction condensate (310 °C, the residence time 7.5 and 10.8 min) from different biomass spices (i.e. corn stover, pea hay, sorghum etc.) They concluded that the methane yield from this process depends on the concentration of hydroxyl-acetate and phenols in the torrefaction condensate, owing to their inhibitory effects.

For the better understanding and optimizing the process integration between torrefaction and AD, the AD of torrefaction condensate produced at different temperatures should be studied. The influence of the varied concentration of the torrefaction condensate on the methane production should also be studied; it helps to understand better the potential level and type of the inhibition to the microorganism. In the earlier studies, it was reported that torrefaction (Liaw et al., 2015) and pyrolysis condensates (Fabbri and Torri, 2016 and Hübner and Mumme, 2015) are inhibitory to the microorganisms at higher concentration. However, it was not clear whether the inhibition is reversible or irreversible, which is essential to be understood when the process is to be scaled up. Furthermore, the methane production and inhibition may be affected by the temperature of AD as it influences the dynamics of microbial population and the chemistry of the condensate (Franke-Whittle et al., 2014 and Diebold, 2000).

The objective of this study was to assess initially the feasibility of AD of the torrefaction condensate from pine wood. Pine is a soft wood, which is widely used in industrial applications like pulp and paper, bioenergy and construction sectors (South and Smidt, 2014), and there is interest to find new uses in various biorefinery applications. For this purpose, AD of the torrefaction condensate produced at different temperatures i.e. 225, 275 and 300 °C, was studied using the bio-methane potential (BMP) batch assays under mesophilic and thermophilic conditions. Furthermore, in order to understand the potential inhibitory effects of the condensate, different organic loading and cyclic batch AD were carried out.

2. Materials and methods

2.1. Biomass

Finnish pine wood was used as a raw material to produce the torrefaction condensate. The selected biomass was a debarked stem wood and received in the form of wood chips (Kuljetusliike Viikari Oy, Narva, Finland). The proximate analysis of the biomass was carried out using thermogravimetric analyzer (TGA; Mettler Toledo TGA 850) following the method as reported elsewhere with little modification (Garcia et al., 2013). Considering the restrictions with TGA operating parameters, the end temperature was set at 800 °C. The proximate analysis of the selected biomass is presented in Table S1.