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Solid fuel production from cattle manure by dewatering using liquefied dimethyl ether

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HIGHLIGHTS

- Dewatering of cattle manure by liquefied dimethyl ether (DME) was investigated.
- Over 98% of water in manure was removed by DME after 70 min under optimum conditions.
- Crude fat in the manure was also removed by DME.
- An 18.1 times increase in the lower heating value of manure was achieved.
- DME dewatered manure had a lower self-ignition risk than thermally dried manure.

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ABSTRACT

Livestock manure is an animal waste that is generated worldwide, and is one of the most abundant waste materials generated in Japan. Its excess application as a fertilizer can cause negative environmental problems; i.e., groundwater pollution and greenhouse gas emissions. When livestock manure is used as a solid fuel, a significant amount of energy is required to remove the high water content by conventional heating, and the resulting dry material has a self-ignition risk that makes it difficult to treat and store. This study focused on an energy-saving dewatering technology using liquefied dimethyl ether (DME) at room temperature, and investigated the dewatering properties of DME and the resulting mass balance of water in cattle manure. The fuel characteristics and the self-ignition risk of the dewatered cattle manure were also investigated.

Under optimum conditions, over 98% of the water and some of the crude fat content in cattle manure could be removed after 70 min (seven batches) at a total DME/initial water ratio of 28.6. The manure was more efficiently dewatered than some other wet biomass such as sewage sludge and vegetable biomass. Moreover, a similarity in the kinetics between thermal drying and DME dewatering also emerged.

The lower heating value (LHV) of DME dewatered manure under these conditions increased to 13.8 MJ/kg, which was 18.1 times that of original cattle manure. The cattle manure dewatered by DME had a lower self-ignition risk than thermally dried cattle manure because of the extraction of crude fat by DME. Therefore, it could be more efficiently produced and safely used as a biomass fuel following DME dewatering.

1. Introduction

Livestock manure is a worldwide animal waste, and is one of the most abundant waste materials generated in Japan. Because

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it contains not only organics but also large amounts of fertilizing components, such as nitrogen and phosphorus, it is mainly recycled by composting. However, in areas with a high livestock density, excess fertilizer application to agricultural land can cause negative environmental problems, including groundwater pollution by nitrate-nitrogen, pathogens, and the proliferation of bacteria resistant to antibiotics used in animals [1,2].

The global greenhouse gas (GHG) emissions from livestock manure that is stored, treated, used as organic fertilizer on cropland, or deposited on pasture are increasing annually [3]. Most of the emissions in each of these stages involve methane (CH_4) and nitrous oxide (N_2O), which have high global warming potential [4].

Because livestock manure is considered a biomass fuel, similar to sewage sludge, it is used to generate thermal and electrical energy in some countries. In the European Union, it is used to produce electricity because of the 'climate neutrality' of its lifecycle [5]. The methane fermentation of livestock manure can produce biogas [6]. However, this requires a long treatment period, and the digested residue, without much volume reduction, requires proper management. To enhance the heating value of the manure in order to produce a solid fuel, dewatering and drying are required. Dry livestock manure has a high heating value and can be totally combusted by incineration [7]. However, livestock manure has a high water content and required a significant energy for drying by conventional heating. The dry material produced has an odor and self-ignition risk that makes it difficult to treat and store [8].

DME has been used commercially as an aerosol propellant, as a sustainable replacement for chlorofluorohydrocarbons (CFHCs), and as a fuel in vehicle engines. China has established the industrial production of coal-based DME that is competitive in price with petroleum-based fuels [9–10]. In Europe, DME has been produced via black liquor gasification, and was successfully used as a fuel in different Volvo DME trucks in the European BioDME project [11]. New dewatering processes have been developed using liquefied dimethyl ether (DME) as a water extractant.

The advantages of DME dewatering processes are based on the following characteristics: (1) DME exists as a gas at room temperature and ambient pressure. Its standard boiling point is −25 °C, and it easily liquefies at 0.51–0.59 MPa at room temperature (20–25 °C). (2) DME has a partial miscibility with water and a high affinity to organic compounds. At room temperature, water is soluble in DME in the range of 7–8 wt.% [12]. After extraction, liquid DME is evaporated by depressurization, and the extracted water is separated. Because of its low boiling point, the recycling processes of DME, including its evaporation and liquefaction, permit the efficient use of unharnessed low-level heat sources. The dewatering energy is almost half of that required by existing thermal drying techniques [13].

This technology can operate at room temperature, and some of the applications [14–23] are presented in Table 1.

In previous studies, most of the contact methods used for extraction were of the fixed-bed extraction type. Regardless of the nature of the sample, the extraction efficiency of water is over 78% under optimized conditions. The extraction efficiency is influenced by extraction time, the DME/initial water ratio and the particle size of the samples. Although it is favorable in terms of energy and cost to extract a greater amount of water at a lower DME/initial water ratio (as close to the theoretical value (12.5–14.3) as possible) and a shorter dewatering time, the process is still influenced by the particle size of samples. The range of extraction times and DME/initial water ratios that have been used are widely distributed in the ranges of 7.3 min–2.0 h, and 14–89, respectively. Coal was considered to be dewatered more easily than a biomass sample; i.e., sewage sludge. This technology has not yet been applied to livestock manure. The livestock manure dewatering properties by DME and the characteristics of the dewatered manure as a fuel remain unknown.

This study investigated solid fuel production from livestock manure following dewatering using liquefied dimethyl ether. This study focused on manure produced by dairy cattle, one of the largest livestock herds in the world. The dewatering efficiency, the water and solid mass balances of dairy cattle manure treated with liquefied DME, the characteristics of the dewatered cattle manure as a fuel, and the self-ignition risk of the dewatered cattle manure were investigated.

2. Materials and methods

2.1. Cattle manure

Dairy cattle manure was collected as a mixture of dung, urine, and bedding straw from the Kyoto Prefectural Agriculture, Forestry and Fisheries Technology Centre in December 2012. The sample manure was a cake-like substance with high water content and containing bedding straw, and was preserved in polypropylene bottles and cooled at 4 °C. Before the DME dewatering experiment, sample manure was homogenized.

The characteristics of the cattle manure samples before DME dewatering are shown in Table 2. The details of the analytical method are shown in Section 2.3. The water and crude fat contents of this sample were 81.8% and 1.5% dry base (D.B.), respectively. The volatile total solid (VTS) and CHN contents and the HHV were 83.4%, 42.7%, 5.7%, and 2.3% D.B. and 16.7 MJ/kg-D.B., respectively. The HHV was approximately 87% that of wood [24]; however, the calculated lower heating value (LHV) was extremely low because of the high water content; therefore, it was not suitable for use as a fuel.

2.2. Experimental setup and conditions

Fig. 1 is a schematic diagram of the DME dewatering experimental setup. The experimental setup was based on a batch mixing type extraction, which differed from the fixed bed extraction systems used in earlier studies (Table 1). However, batch-mixing extraction is important and can easily determine the dewatering properties of samples and predict the dewatering kinetics in fixed bed extraction using a tank-in-series model during the next stage. This experimental setup consisted of four main parts: (1) a vessel for storing liquefied DME (Vessel 1, TVS-1-100, 500 cm^3, Taiatsu Techno Corp., Saitama, Japan); (2) a vessel for dewatering (Vessel 2, HPG-96-3, 26.5 mmφ × 238 mm, Taiatsu Techno Corp.) with an impeller (H:50 mm × L:15 mm × D:2.0 mm), a stirring motor (VP motor, Taiatsu Techno Corp.), and a stirring speed controller (Taiatsu Techno Corp.); (3) a vessel for storing the separated liquid (Vessel 3, HPG-96-3, 100 cm^3, Taiatsu Techno Corp.); and (4) a trap column (HPG-10-5, 11.6 mmφ × 190 mm, Taiatsu Techno Corp.).

Since it was necessary to bring the cattle manure into contact with liquefied DME under ideal conditions, a 10.0 g spherical sample (diameter approximately 26.5 mm) was packed into vessel 2. Liquefied DME was produced by cooling pure gaseous DME (Sumitomo Seika Chemicals Co., Ltd., Osaka, Japan) to −12 °C with ethanol and ice, and was then pressurized at 0.2 MPa and stored in vessel 1. Vessel 1, containing the liquefied DME, was then placed into a bucket of water and its temperature was maintained at 25 °C. Vessels 2 and 3 were preliminarily purged with 0.3 MPa DME gas. Under pressurization at 0.7 MPa using nitrogen gas, liquefied DME was transferred to vessel 2.

After the cattle manure sample was immersed in the liquefied DME in vessel 2, the dewatering time per batch, stirring speed, and the number of batch treatments (DME/initial water ratio was