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Anaerobic digestion and gasification hybrid system for potential energy recovery from yard waste and woody biomass

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ABSTRACT

There is a rapid growing interest in using biomass as an alternative source for clean and sustainable energy production. In this work, a hybrid system was developed to combine anaerobic digestion (AD) and gasification for energy recovery from yard waste and woody biomass. The feasibility of the proposed hybrid system was validated experimentally and numerically and the energy efficiency was maximized by varying energy input in the drying process. The experiments were performed in two stages. At the first stage, AD of yard waste was conducted by mixing with anaerobic sludge. At the second stage, co-gasification was added as post-treatment for the AD residue for syngas production. The co-gasification experiments of AD residue and woody biomass were conducted at varying mixing ratios and varying moisture contents of AD residue. Optimal energy efficiency was found to be 70.8% at mixing ratio of 20 wt% AD residue with 30 wt% moisture content. Two kinetic models were then adapted for prediction of biogas produced in AD process and syngas produced in gasification process, respectively. Both experimental and numerical results showed that full utilization of biomass could be realized to produce energy through the combination of these two technologies.

1. Introduction

Global temperature has been on a general rising trend for the past 100 years and there is an increasing demand for seeking sustainable and environmental-friendly energy source to replace fossil fuels [1]. In Singapore, more than 196000 tonnes of sludge, 362000 tonnes of horticultural waste and 370600 tonnes of wood have been generated in 2015 with the recycling rate of 13%, 66%, and 79% respectively [2]. Yard waste, usually produced in gardens and zoos, has considerable amount of carbon-rich organic matters which could be converted to value-added product by chemical or biological treatment [3–5]. Since there is an increasing emphasis on seeking reliable energy source and decreasing the reliance on fossil fuel dependent energy generation processes, biogas generation from anaerobic digestion (AD) of biomass is rapidly gaining interest in the energy industry [6,7]. AD is a biological process in which biodegradable material is decomposed into biogas by microorganisms in an oxygen free environment. The AD product, biogas, mainly consists of methane (CH_4) and carbon dioxide (CO_2). A wide range of organic matters has been used for AD process, such as municipal solid waste, industrial organic waste, agricultural waste and animal manure [8]. The energy generated from AD has several advantages over other renewable energies. The production of biogas from AD is storable much unlike wind or solar energy where the energy generation ability fluctuates greatly throughout the day. Thus, it is not a critical issue in the stability of the energy generated from biomass and it can contribute consistently to the energy needs of the country [9]. Furthermore, the produced biogas can also be used for various other downstream processes. Currently, about 55% of produced biogas are used for ammonia production for fertilizer production and the second most prominent usage of biogas are refineries for the hydrogen [10]. The basic principles and operating parameters of AD have been intensively analysed and discussed, such as pH, volatile acids/alkalinity ratio, inoculum to substrate ratio, temperature, hydraulic retention time and non-ideal mixing conditions [11–15].

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Although AD has several advantages over other waste disposal methods, there is still much room left for improvement on the post-treatment of residue generated from AD process. The waste volume reduction of anaerobic digestion process is not as good as that of the thermal treatment process. The residue generated from AD of anaerobic sludge may contain toxic microorganisms and heavy metals which make it unsuitable for direct landfill or further utilization as fertilizer [3]. In addition, there is still considerable amount of organic matters left in the residue at the end of AD process since lignin fraction is hard to be broken down by microorganisms during AD process [16].

To improve energy recycling efficiency and realize full utilization of biomass, gasification is added as post-treatment for AD residue [17]. Gasification is a thermochemical conversion process which converts biomass through partial oxidation into a gaseous mixture of syngas consisting mainly of hydrogen (H_2), carbon monoxide (CO), methane (CH_4) and carbon dioxide (CO_2) [18,19]. It is considered as one of the most efficient ways of recovering the energy embedded in biomass with less toxic emission compared with incineration. The composition of the syngas produced from gasification depends on several parameters which have been widely reported by literature, such as fuel composition, gasifying medium, operating pressure, reactor temperature, equivalence ratio, moisture content of the feedstock and the design of gasifier [20–24].

Several studies have proved the feasibility of the hybrid process which combines these two technologies by simulations on the real operation data of one full scale biogas plant and one full scale biomass gasification plant [25,26]. Maximum exploitation of the energy embedded in organic waste could be reached by this hybrid waste disposal process. However, there is no experimental result being reported to validate this concept. In the previous work of our research group, it has been proved that it's feasible to co-gasify 20 wt% of sewage sludge with 80 wt% wood chips for energy production [27]. In this study, a two-stage hybrid system which combines AD and gasification for energy recovery from yard waste and woody biomass has been proposed and investigated experimentally and numerically for the first time. At the first stage, AD of yard waste was conducted by mixing with anaerobic sludge. At the second stage, the digested solid residue was co-gasified with woody biomass for syngas production. Energy performance in this hybrid system was evaluated taking into account energy input and output in AD process, energy input and output in gasification process and energy input for drying process. Two kinetic models were also adapted for prediction of produced biogas in AD process and syngas yields in gasification process, respectively. Both experimental and simulation results proved the feasibility of the proposed hybrid system. In addition, the energy efficiency and quality of the produced gas were optimized by varying energy input in drying process.

2. Materials and methods

2.1. Description of two-stage process

The proposed hybrid system which combines AD and gasification is shown in Fig. 1. The anaerobic sludge and fallen leaves were mixed manually before adding into the high solid anaerobic digestion (HSAD) reactor. During the course of digestion, produced biogas was diverted to a gas meter in order to record the amount of produced biogas. Gas sampling was conducted periodically to analyse the biogas composition. In addition, the AD residue was removed from the reactor for drying to certain moisture content. After which, the dried AD residue was mixed with woody biomass and then fed into the gasifier for syngas production. Produced syngas was diverted to a gas analyser to record lower heating value (LHV) and component compositions. To calculate energy efficiency of this hybrid waste disposal system, the summation of feedstock input energy for both AD and gasification process, electricity input for both AD and gasification system, and extra energy input for drying process were considered as total energy input. Energy output included both biogas generated from AD and syngas generated from co-gasification.

2.2. Experimental setup and sample characterization

2.2.1. Sample characterization

At the first stage, two main inputs used for AD were fallen leaves and anaerobic sludge. The fallen leaves were collected from yard waste of National University of Singapore. After which, they were then shredded and homogenised into smaller pieces (approximately 2 cm in length). The anaerobic sludge was used as inoculum and it was collected from Public Utilities Board (PUB) Ulu Pandan Water Reclamation Plant with a pH value of 7.62. The

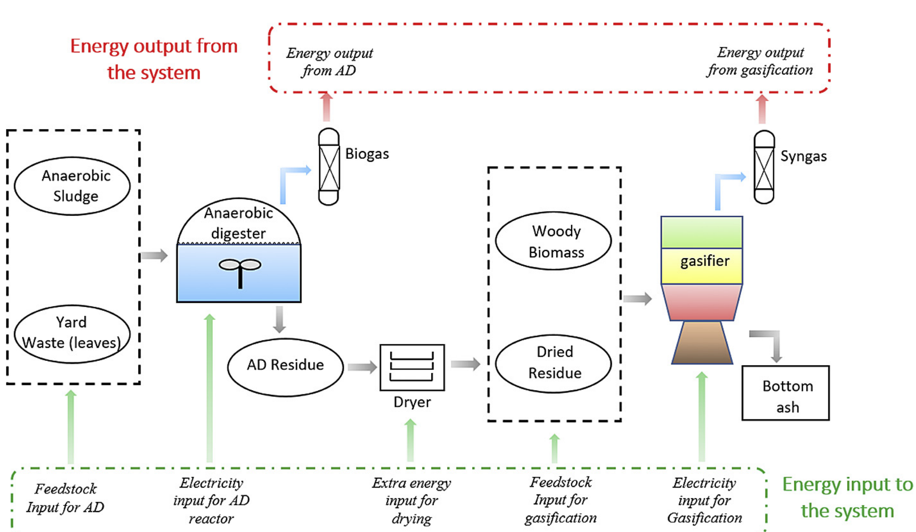

Fig. 1. Process flowsheet of two-stage hybrid system.