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Research paper

A combination anaerobic digestion scheme for biogas production from dairy effluent—CSTR and ABR, and biogas upgrading

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Anaerobic digestion of low-strength dairy waste water was used for the production of biogas which is aimed at serving as a concentrated carbon dioxide (CO_2) source for further methanation. Using hydrogen (which can be produced via electrolysis using renewably sourced electricity), the CO_2 fraction of the produced biogas can be used as a mechanism to store surplus electricity by the Sabatier process, which converts the CO_2 fractions to methane (CH_4), i. e. synthetic natural gas. This study investigates the use a combined reactor scheme for the anaerobic digestion of dairy waste water, and the further upgrading of the biogas products from the process. A combination pilot scale process was established with a 90 d start-up time using a 1 m^3 continuous stirred tank reactor (CSTR) and a 0.2 m^3 baffled reactor (ABR) in series. The system was fed at constant retention time in the ABR of 1.6 d and with varying substrate organic loading rates between 1.25 and 4.50 kg m^{-3} d^{-1}. The average chemical oxygen demand (COD) removal was 82% with a biogas yield of 0.26 m^3 kg^{-1}. The use of the derived biogas for the Sabatier process to convert hydrogen into CH_4 showed no disadvantages compared to synthetic gas mixtures. The combination of CSTR and ABR overcame the individual disadvantages of both reactor types. The investigated anaerobic digestion system can be further optimized and adopted to replace conventional waste water treatment systems.

1. Introduction

Anaerobic baffled reactor (ABR) systems have been widely applied as high rate digesters especially in developing countries where they have been used to meet on-site sanitation goals [1]. Numerous research papers have been published in the last two decades which have reported the potential advantages of the use of ABR as an excellent anaerobic digestion system for low- and high-strength waste water [2–6] and for the treatment of complex organic waste streams [7,8]. The simplicity and inexpensiveness of the ABR system, coupled with its non-requirement of moving parts or mechanical mixing for the anaerobic fermentation process has also strengthened the potential benefits associated with the use of this anaerobic digestion reactor system [9].

Due to the construction of the ABR (as a series of up-flow and down-flow sections), this reactor type enables an internal phase separation, i. e. different process parameters can be maintained and manipulated in the different reactor compartments. This selective process differentiation in the reactor compartments could enable hydrogen production at low residence times, and improved overall methane yields from the anaerobic digestion process as reported in Refs. [10–12]. The industrial applications of the ABR scheme have however been mainly limited to waste water treatment [1] and have not yet been expanded for use in the digestion of other organic residue streams i. e. animal excreta and industrial organic residues (such as dairy and food processing waste).

Dairy waste water effluent is generally regarded to contain a high organic load and is considered a useful substrate for anaerobic processes aimed at methane production [13,14]. The effluents from dairy processing plants (producing fresh milk and yogurt) have however been observed to be characterized by having a low chemical oxygen demand (COD). Typical COD values of the effluent in milk processing dairies are 2–10 kg m^{-3}, with up to 70 kg m^{-3} reported for whey waste water [9,15]. Owing to such low COD values, the effluents of milk processing dairy plants can be considered as unsuitable for treatment in a conventional

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continuous stirred tank reactor (CSTR)-type biogas plant [16]. Effluents which are considered as ”low-strength”are therefore often treated in high rate anaerobic digesters like upflow anaerobic sludge blanket (UASB) or biofilm reactors. These types of reactors use different hydraulic (HRT) and solid retention time (SRT) distributions, which favour the slow growing *methanogenic archea* thus improving methanogenesis [17]. These reactor designs are however limited when dealing with substrates which contain high amounts of fats or solids. This is mainly due to transfer restrictions brought about by the absence or lack of stirring or mechanical mixing components. Solids with densities higher than that of water usually sink and accumulate in the first chamber, with the fat contents of usually resulting in the formation of floating layers in the digester [1]. In both cases, organic components become inaccessible to the microbial community. Limitations to the use of currently available, cost effective anaerobic digestion treatment routes for low strength dairy waste water but with a high fat and solids content can therefore be observed and needs to be addressed to ensure the proper utilization of this valuable resource and to prevent potential environmental degradation processes (i. e. euthrophication of water bodies) associated with the non-treatment and disposal of such residues. This study investigates the combination of the CSTR and ABR schemes (in series) as a useful means of overcoming the disadvantages of both systems, with the goal of facilitating the use of this stream as a useful carbon source for the methanation process.

The paper will not only highlight the methanogenic processes related to the bacterial flora of the digestion process i. e. eventually leading to the production of biogas (a mixture of methane (CH_4), carbon dioxide (CO_2) and other trace gases such as hydrogen sulphide (H_2S) and ammonia), but will also look at the incoporation of an additional thermochemical process (Sabatier reaction) into the anaerobic digestion system with the overall goal of optimizing the overall methane (and hence energy) yields from the preceding digestion process.

The methanation of CO_2, also known as Sabatier process, is a thermochemical reaction at increased pressure and temperature using Nickel or Ruthenium catalyst. Previous research has demonstrated the use of this process for the conversion of the CO_2 fractions of anaerobically derived biogas to CH_4 With regards to the efficiency of the Sabatier process when used for biogas CO_2 conversion, significant poisoning of the reaction catalyst (Nickel) was demonstrated to occur in the presence of small amounts of hydrogen sulphide (H_2S [18]. A reduction of the biogas H_2S levels (i. e. via desulphurisation processes) is therefore essential before the biogas can be applied for the thermochemical methanation process. Additionally, the influence of other trace substances, like ammonia and siloxanes contained in the anaerobically derived biogas on the Sabatier process and the reaction catalysts are unknown. And have not been extensively identified [19] due to the difficulty related to analysing such trace components using conventional biogas analysis systems [20].

The usage of actual biogas mixtures is therefore important to take into account, since it would influence the feasibility of such anerobic-thermochemical combination systems in practice. This is especially important since the use of, and integration with dairy waste water digestion was found to be lacking in the literature. With the presence of contaminants i. e. cleaning agents and disinfectants used for hygienic food processing plants potentially negatively affecting the anaerobic and thermochemical process, this study provides a useful assessment of their influence on both procesess.

This study aims to highlight the importance of local residue streams from industrial processes for both, energy generation and as a carbon source. In a future of 100% renewable energy scenario, electricity will be an important primary energy carrier [21]. To satisfy the needs of the transportation and industry sector, it is expected that hydrogen will be produced in decentralized units using renewable energy sources like wind and solar [22] and converted into fuels with better properties like CH_4 and methanol [23]. This paper initially considers methods to improve the biogas yields from a currently underutilised dairy effluent water, and further assess the upgrading of the energy value (through an increase in the methane outputs) of the anaerobically derived biogas through the integration of the Sabatier process. The work therefore aims to demonstrate at a lab scale concepts of decentralised biogas production and upgrading with the intention to facilitate matching the biogas quality to natural gas grid standards as previously reported in the literature [24–26]. In addressing those issues the paper will also highlight the use of biogas production from a wide range of substrates. Such substrates could the be a local carbon source for the storage of renewable generated hydrogen.

2. Materials and methods

The experimental setup used in this study is shown in Fig. 1. It includes sections for: biogas generation, conditioning, and upgrading. All values for feed strength, specific gas production and organic loading rate (OLR) are based on COD.

2.1. Anaerobic digestion using the CSTR-ABR combination system

2.1.1. Substrate

The effluent water of a local dairy plant (Osterhusumer Meierei Witzwort EG, North Frisia, Germany) was used as primary substrate for the AD process. It was delivered once a week and stored at ambient temperatures in a 1 m^3 intermediate bulk container. From here, it was pumped once a day into the well stirred 0.25 m^3 feed tank.

At the dairy plant production site, the effluent was collected from a buffer tank, which is used to feed the dairy's conventional (aerobic) waste water treatment plant and to avoid shock loading events to it. The dairy waste water initially contained varying amounts of NaOH and H_3PO_4, used in the plant cleaning processes. These were however neutralised before this tank. The phosphate content resulted in a high acid base capacity of the dairy waste water mixture. The chemical oxygen demand (COD) of the waste water sample was analysed after delivery to the experiment site. The COD levels of the substrate were observed to usually fluctuate between 2.5 and 5.0 kg m^{-3} during the reactor operation. More extreme fluctuations for the substrate COD were however periodically recorded as indicated in Table 1 which shows the dairy waste water characteristics recorded during one year of operation. The levels of the dairy waste water COD, nitrate, and phosphorus levels were determined using Hach Lange cuvette tests.

2.1.2. Anaerobic digesters

A 1 m^3 CSTR and a 0.2 m^3 ABR were used in series for this study. The CSTR was temperature controlled (operating temperature was 38 °C) using a Pt-100 sensor, a micro-controller and four 1 kW heating rods, which were inserted from the top of the vessel into the liquid. The temperature probe was also equipped with a pH sensor. The whole steel vessel was properly insulated to maintain the temperature profile and prevent temperature loss from the reactor.

A level drain was used to transfer the effluent to the ABR system by gravity. Each of the four chambers was controlled individually using Pt-100 sensors and heating foils fixed to the external reactor walls. The downflow-to-upflow ratio was 1:2. A siphon was used to drain the effluent to the sink. Each chamber was equipped with

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