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Feasibility of coupling hydrogen and methane production during sewage sludge digestion

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Abstract Anaerobic digestion is a technology widely used for the stabilisation of sewage sludge in wastewater treatment plants (WWTP). This technology presents several advantages such as the production of energy and the use of this energy to cover the demand of the treatment plant. However, sludge digestion systems may not produce an enough amount of biogas to cover a great fraction of the total energy demand. In the present manuscript is evaluated the introduction of a fermentative hydrogen phase and the effect produced in the system in terms of the energy balance. Food waste were considered as carbohydrate rich co-substrate and batch fermentation of this process is evaluated. The system was modelled using SuperPro designer considering conventional waste activated sludge system for the treatment of wastewater whereas the sewage sludge line was studied under mesophilic regimens. The mass and energy balance indicated an increase between 20 - 60% in the whole valorisation process, reporting as suitable this alternative when using digestate as inoculum source for starting-up the hydrogen process.

Keywords: Enhancing performance, biogas productivity, energy efficiency

1. Introduction

Anaerobic digestion is a technology that has demonstrated great environmental benefits regarding the treatment of different organic wastes. These materials that are susceptible of uncontrolled degradation can cause several environmental problems regarding water pollution and offensive odours (Sarkar & Chourasia, 2017). However, the high water content of this type of wastes make them suitable candidates for valorisation under anaerobic digestion. Biogas is produced as one of the main valuable stream from the process and a liquid slurry is obtained which is usually valorised as an organic amendment.

One of the major factors that set constraints to the further implementation of this technology is the high capital investment and installation costs. These are usually too high for small and medium size farmers to become a real treatment alternative for manures. An option that may be of easier implementation would be the modification of existing treatment units in an attempt to increase organic loading of already operating digesters. This way, an increase in biogas production is obtained thanks to the synergies associated with co-digestion of different substrates and allows the share use of these facilities and increasing thus its productivity (Sompong et al., 2012).

The availability of different substrates obviously relies of the location of the treatment plant. In urban centres a common option is the combined treatment of sewage sludge and food wastes, but other options also consider centralised digestion plants treating a great variety of substrates. Case studies have been reported by Sembera et al. (2019) evaluating food and dairy wastes co-digestion. Others are related to the addition of different substrates in waste water treatment plants (WWTP) and large scale digestion plants (Balussou et al., 2012; Mattioli et al., 2017; Macintosh et al., 2019; Masłoń et al., 2020). In any case, there are undoubtly benefits regarding the use of already existing installations which may be adapted for treating different waste stream and therefore get additional revenues from electricity production.

Anaerobic digestion takes place in a sequential set of reactions were acid intermediaries are generated and then subsequently transformed into biogas. Modifications in reactor performance are experienced when the process affront sudden organic over loadings and temperature variations, affecting biogas evolution and composition. Organic overloading of the system is easily attained if changes in the feeding recipe are experienced, as it would be an unexpected increased in biodegradability of the substrate or higher solid content of the feed. Two-stage digestion has been proposed as a buffering strategy and to stabilise process performance (Schievano et al., 2012; Wikandari et al., 2018; Rajendran et al., 2020). However, the implication of an additional reactor being installed results less attractive.

Fermentative hydrogen production has been extensively studied in recent years to favour reactor dynamics to sustain a specific microflora (Akinbomi et al., 2015; Mañunga et al., 2019; Okonkwo et al., 2020). The two-phase process dedicated to hydrogen production and methane production in the second stage may be proposed as a feasible alternative to enhance plant performance and justify the use of an additional tank reactor capable of producing a biofuel with high calorific value. Acids intermediaries produced in the fermentative H_2 phase and remaining in the reactor liqueur can be anaerobically treated in a second fermentation stage. Numerous report papers indicate the suitability of obtaining a hydrogen producing microflora from the same anaerobic methanogenic system (Gómez et al., 2006; Fernández et al., 2015; Wang et al., 2020). Even though microbial shifts were reported as a recurrent problems proposing costly alternative for avoiding it, as it is heat shock and acidification, recent documents have reported on stable operation when recycling streams from the methanogenic reactor are introduced for controlling pH and maintaining an active population of hydrogen producing organisms (Cavinato et al., 2011; Luo & Wong, 2019).

In the present manuscript an evaluation of the expected performance of a two-stage digestion system intended for producing H_2 in the first stage was evaluated using SuperPro Designer, v10 version. The evaluation considered a conventional WWTP using waste activated sludge as biological water treatment and anaerobic digestion as treatment for sewage sludge. Description of the performance is presented given assumptions obtained from the literature.

2. Material and methods

2.1. Plant description and assumptions

The WWTP was evaluated considering the process under mesophilic conditions. The mass and energy balance were calculated to evaluate the benefits of integrating a hydrogen fermentative reactor operating under batch conditions along with the conventional process for sewage sludge digestion. The hydrogen produced from the first phase is derived from batch fermentation attained for 24 h period. The process is assumed to use digestate as inoculum without applying any type of pre-treatment, based on report of Wang et al. (2020) and Luo et al. (2011) indicating that inoculum pretreatment was not effective on permanently inhibiting methanogenesis and homoacetogenesis.

The calculation is based on a conventional WWTP for 150000 equivalent inhabitants (Eq. Inh.) using assumptions of Martínez et al. (2019). The hydrogen produced from the batch fermentative system is mixed with the biogas produced from the anaerobic reactor. The acidified food waste is used as co-substrate for the sewage sludge digester. Calculation of gas production was based on hydrogen and methane yields reported by Yuan et al. (2019) and Kuang et al. (2020) using as average value 196 mL H_2/g VS (VS stands for volatile solids – values reported for food wastes), and values reported by Cabbai et al. (2013) and Keucken et al. (2018) – 483 mL CH_4/g VS, for food wastes and a value of 268 mL CH_4/g VS for sewage sludge.

The sludge line consisted of the primary settler and the gravity thickener where the primary sludge is concentrated and subsequently mixed with the secondary sludge. Assumptions for this section were based on García-Cascallana et al. (2019, 2021). The anaerobic digester treats this mixture at a hydraulic retention time (HRT) of 20 d. The sludge line considering the thickening of primary sludge and secondary sludge, using in the first case a gravity thickener and an air flotation system in the second one. Anaerobic digestion treats the mixture of sludge in the base scenario and is assumed to treat the effluent of the first fermentative hydrogen stage in the modified scenario.

Plant parameters considered for evaluating performance were, biogas production, low heating value of biogas, digestate volumetric production and energy produced from biogas valorization (electricity and thermal energy by means of a CHP unit – combined heat and power).

3. Results and discussion

The characteristics of the process are detailed in Table 1.

Table 1. Characteristics of plant performance for the base scenario

Parameter	Value
Incoming wastewater flow (m^3/d)	52500
Primary sludge (m^3/d)	61.1
Waste activated sludge (WAS) (m^3/d)	70
TS/VS primary sludge (g/L)	60/48
TS/VS WAS (g/L)	55/44
Biogas (m^3/d, STP)	101
Electricity production (kW)	225

The incoming flow of waste water is initially treated for removing high particle size materials, and it was assumed that 2% of the volumetric flow was separated from the main stream along with high particle size material. From the primary settler is obtained sewage sludge being posteriorly concentrated by means of the gravity thickener. The conventional aerobic treatment is assumed to treat wastewater and the waste activated sludge is purged from the system at a concentration of 2.5 g/L. After applying air thickening the sludge solid content is increased and subsequently mixed forming a single sludge stream which is digested in the mesophilic anaerobic digester.

Figure 1 represents a schematic model of the WWTP considered. In this scheme main treatment units are visualized for the production of primary and waste activated sludge. The aerobic treatment of wastewater considers an 80% mass conversion of organics into cell material giving rise to the secondary sludge purged from the treatment unit. The sludge is treated by anaerobic digestion considering a HRT of 20 d. The energy contained in biogas produced attains a value of 2020.9 MJ/h (561.4 kW) based on previous assumptions.

The installation of the additional equipment for treating source sorted food wastes in the plant must then consider the transport to the facility, storage of this material and shredding in order to obtain a slurry fraction capable of being pump into the digestion facility without causing pipe clogging.

The addition of food waste into the digestion system to attain a VS proportion from 10 – 30% in the digester feed leads to a waste mass flow between 4.4 and 13.4 t/d. In order to couple batch hydrogen fermentation and continuous digestion, then 3 small fermenters will be needed with a size between 9 and 27 m^3 of working volume. The additional feed would produce an additional amount of energy in the range of 480 – 1445 MJ/h (134 – 400 kW) when considering H_2 and CH_4 produced from food wastes added. The extra amount of electricity produced will then increase in 21 – 64% based on the percentage of food waste added to the system and a 36% efficiency in electricity conversion. However, the LHV of biogas expressed in terms of volume is significantly reduced due to the small density of the hydrogen molecule, thus for the case studied the LHV of biogas is reduced from 21.5 to 18.8 MJ/m^3

4. Conclusions

Two-phase digestion results in a suitable alternative for increasing WWTP performance. The installation of a batch fermentation unit dedicated to obtaining hydrogen from food wastes as co-substrate allows an increment in plant electricity production and therefore aids in covering energy demand. The co-substrate allows an increase in the energy content of biogas per unit mass. Further estimations would be performed to establish the operating sequence of the batch fermentation system and the additional energy demand.

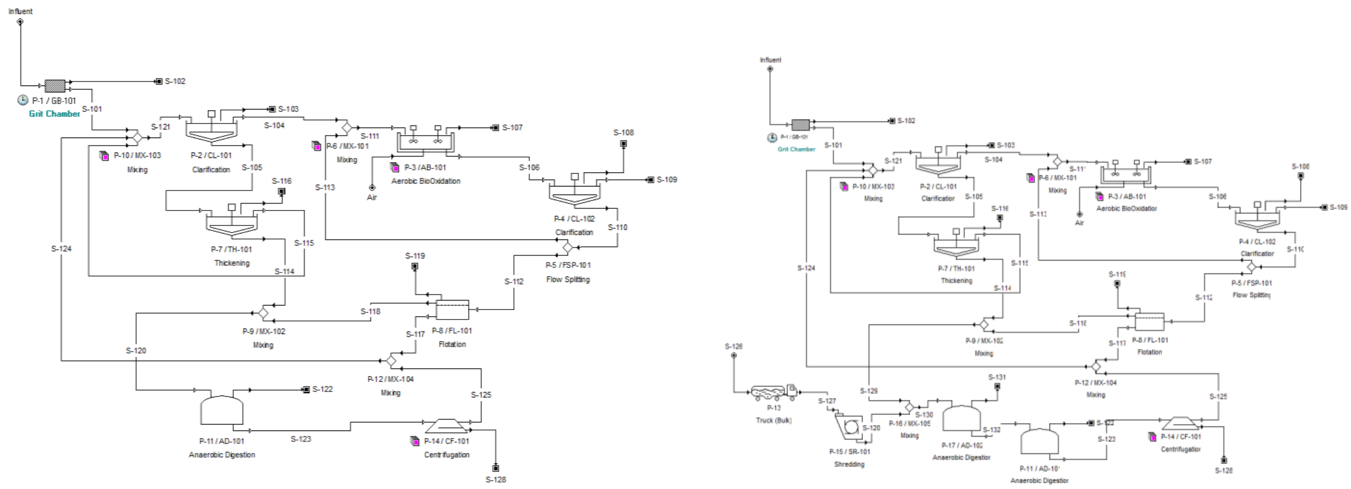

Figure 1. Schematic representation of the conventional WWTP considering anaerobic digestion for the treatment of sewage sludge (left figure) and the introduction of a batch fermentation system for producing hydrogen (right figure).

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