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Simulation Study for Optimising the Operating Conditions of Anaerobic Co-Digestion for Sewage Sludge

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Anaerobic digestion (AD) is a process that converts biodegradable wastes into methane (CH_4) gas, reducing the waste's size efficiently. The methane gas can be used as biofuel for power generation due to its explosive properties. The biogas could be upgraded to bio-compressed natural gas (Bio-CNG), which could be utilised as a fuel in the community. Biogas or methane yield from the AD process of sewage sludge (SS) usually is undesirable due to the lack of vital components, such as carbohydrates, proteins and fats, with higher inert substances or moisture content. Therefore, the optimisation of the AD process for SS feedstock is needed to increase its biogas yield. In this study, the anaerobic co-digestion (ACoD) with other wastes, such as corn silk (CS), food wastes (FW), cattle manure (CM), and palm oil mill effluent (POME), is investigated through a simulation model in SuperPro Designer. The biogas upgrading technologies, namely chemical and water scrubbing, are studied in this model to investigate the biogas purification efficiency for producing methane-rich biogas gas that meets international standards (>90 % CH_4 and <1,000 ppm H_2S).

1. Introduction

In the daily operations of wastewater treatment plants (WWTPs), an enormous amount of sewage sludge (SS) is produced as a side product. The wastewater sources vary from domestic to non-domestic, affecting the quality of SS being produced (Kacprzak et al., 2017). Commonly, SS contains a high amount of organic matter and solid content, depending on the origins (Nuamah et al., 2012). As the population increases annually, the quantity of SS produced from WWTPs increases, resulting in public concerns about the waste management of the side product. Moreover, the high demand and usage of fossil fuels have caused toxic pollutants due to the unstoppable emission of greenhouse gases (GHG). The fossil fuel supply depletes rapidly due to unstoppable consumption. Anaerobic digestion (AD) is a technology that converts organic wastes into valuable products such as biogas riched in methane and nutritious fertiliser (Tan et al., 2022). Amado et al. (2021) studied the simulation of AD based on pig manure and its environmental impact via Life Cycle Assessment. Anaerobic co-digestion (ACoD) is suggested for substrates that are not easily digestible to increase biogas production or methane yield. To date, several investigations on the impact of ACoD on various wastes have been done by researchers either in experiments or simulations. Szaja et al. (2021) investigated the combined AD system experimentally for energetic brewery spent grain (BSG) used in ACoD of BSG and SS. The results obtained found that the cavitated BSG with carrier compounds like MPW has significantly increased biogas and methane yield. Zahedi et al. (2020) proposed an ACoD study on the valorisation of wine distillery wastewater (WDW) and SS. According to the results, the ACoD of two substrates achieves higher methane production than the AMoD of SS alone. A simulation work for the ACoD to upgrade biogas production was done by Inayat et al. (2019) using Aspen Plus simulation software. The results show that the optimum ratio for the ACoD of the substrates is 50% wastewater, 25 % cattle manure, and 25 % biomass (date seed) with 47.85 mole% CH_4 and 20.80 mole% CO_2 in the gas stream, indicating the biogas in the stream. Adedeji and Chetty (2021) studied the co-digestion of SS with

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wastewater from the brewery, dairy and sugar industries. The results found that the sugar and dairy wastewater has a high potential to be co-digested with SS for maximum methane production in 21 d HRT.
By blending the SS with co-substrates, the vital nutrients needed for the microorganisms in every digestion stage will be increased significantly, and the inhibitors can be stabilised efficiently (Chow et al., 2020). In this work, the AD process for SS feedstock is simulated using the SuperPro® Designer (2020) simulation software to investigate the biogas production rate in the system. The work aimed to optimise the operating parameter for the co-digestion of SS with various biomass feedstock. Several biomass feedstocks, such as corn silk (CS), food waste (FW), cattle manure (CM) and palm oil mill effluent (POME), are simulated for studying the most suitable co-substrates. The hydraulic retention time (HRT) and feed ratio between SS and co-substrates in the AD process are investigated for maximising biogas production in the co-digestion process. In addition, chemical and water scrubbing technologies are simulated with th e AD process for biogas upgrading to observe the methane purity in the biogas, that meets international standards (>90 % CH_4 and <1,000 ppm H_2S) as stated by Kadam and Panwar (2017), and U.S. EPA (2016).

2. Methodology

The AD simulation model for SS's anaerobic mono-digestion (AMoD) is developed using the SuperPro® Designer (2020) simulation software based on the simplified mass-based ADM1 (Weinrich and Nelles, 2021), as shown in Figure 1. The AD model is further developed into anaerobic co-digestion (ACoD) of SS with CS, FW, CM and POME to investigate the effects of ACoD on biogas and methane synthesis, as shown in Figure 2. The organic compositions in the feedstock are defined based on the literature reviews, such that SS (Inoue et al., 1996), CS (Nawaz et al., 2018), FW (Khan and Kaneesamkandi, 2013), POME (Gozan et al., 2018) and CM (Budiyono et al., 2011). Besides, biogas purification technologies, such as chemical scrubbing and water scrubbing, were constructed in the AD models to evaluate the biogas purification efficiency and obtain methane-rich bio-CNG. All the simulation models are developed using SuperPro® Designer (2020). Sensitivity analysis, including the effects of HRT and feed ratio, was conducted on the two selected ACoD models to determine the sensitivity of the models constructed.

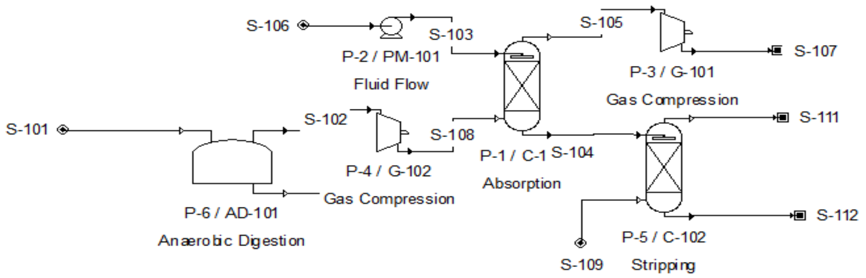

Figure 1: AMoD Model with biogas upgrading technologies

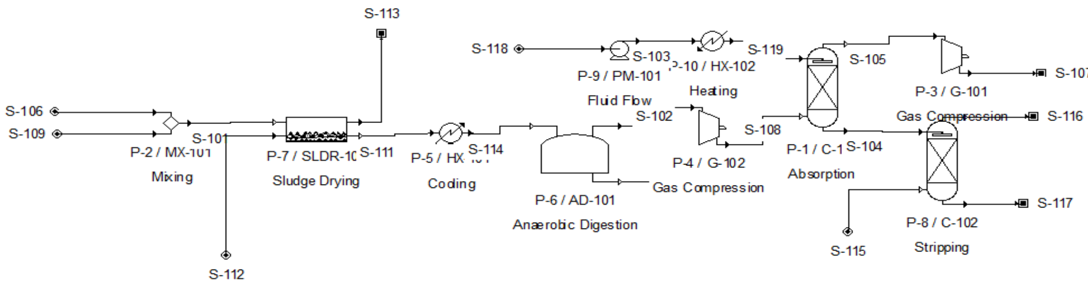

Figure 2: ACoD Model with biogas upgrading technologies

The AD in every ACoD and AMoD model operates under the mesophilic condition of 35 °C and atmospheric pressure. For the chemical scrubbing technology, 30 wt% of MEA solution is used in the absorber, operating at 40 °C, while water is used in the stripper unit that operates at 120 °C. The operating pressure for both units is set at 1.5 bar (Vo et al., 2018). On the other hand, the absorber and stripper in the water scrubbing technology operate at 3 bar and 1.013 bar (Rotunno et al., 2017). Air is used in the stripper unit of this technology. Some auxiliary equipment like pumps, compressors, mixers and dryers are added for a more comprehensive simulation model.

3. Results and discussions

3.1 Simulation model validation

After the development of complete AD models, the SS is used as the primary feed to study the mono-digestion behaviour of SS under a mesophilic condition with a HRT of 30 d. The biogas generated from the anaerobic digester is analysed and compared with the typical biogas composition proposed by Zelepouga et al. (2010), as shown in Table 1. Based on the simulation results, the application of the AD model by Weinrich and Nelles (2021) is reasonable with the overall biogas composition generated. The mass composition for significant components like carbon dioxide (CO_2) reaches 47.69 % within the literature range, while the methane content is close to the minimum value of 49.70 %. Moreover, trace components like hydrogen sulphide (H_2S) meet the biogas properties of 0.048 %. Since the source of sewage sludge varies in many categories ranging from residential areas, industrial areas and countries, this may result in divergent components present in the SS, affecting the AD process with various trace components. Thus, the formation of a small portion of ammonia in the biogas is reasonable based on research.

Table 1: Biogas composition from simulated AD process of SS

Parameters	This Study	Zelepouga et al. (2010)
	Percentage (%)	
Ammonia (NH_3)	2.56	traces
Carbon dioxide (CO_2)	47.69	25 - 50
Hydrogen Sulphide (H_2S)	0.048	0 - 3
Methane (CH_4)	49.70	50 - 75
Nitrogen (N_2)	0	0 - 10
Oxygen (O_2)	0	0 - 2
Hydrogen (H_2)	0	0 - 1

3.2 Comparison between AMoD and ACoD of SS

The effects of ACoD are determined by mixing the SS with other feedstocks at a ratio of 2:1, operating under mesophilic conditions at 30 d HRT. After the results are obtained, the data is compared with the AMoD of SS. The results trend, as shown in Figure 3, follows the research done by other researchers that the overall biogas production and methane yield in ACoD of SS increases significantly compared to the AMoD of SS. These results show that implementing ACoD provides higher nutrient contents and stabilises the AD environment effectively, thus enabling higher microbial activities in the AD and more biogas and methane synthesis. Among the co-substrates, the CS acquires the highest amount of biogas produced at 5,512.05 kg/batch, while the combination of POME and SS scores the lowest amount with 887.58 kg/batch among the ACoD process. For the methane content, the SS+FW group achieves the highest value at 49.62 % compared to 36.86 %, 36.92 % and 48.06 % for CS, CM and POME. Due to the concern of operating and capital costs, the SS+FW combination is selected for further investigations on biogas upgrading technology comparison and sensitivity analysis compared to the SS+CS group.

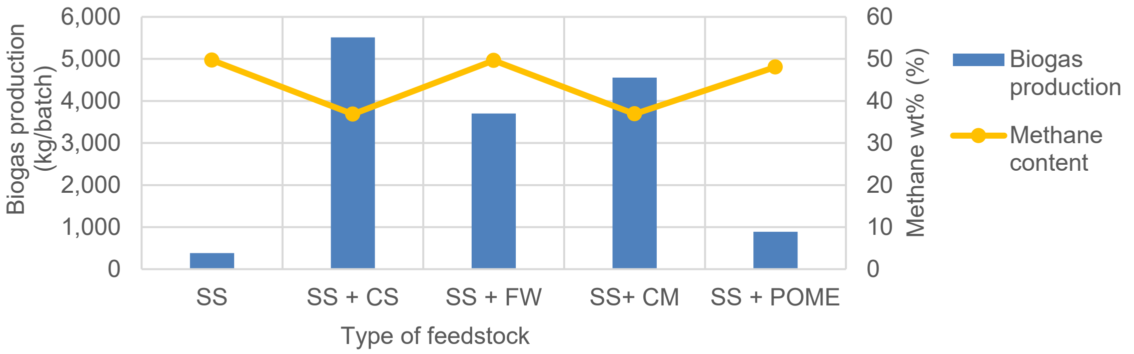

Figure 3: Comparison between AMoD and ACoD of SS under mesophilic conditions

3.3 Biogas upgrading technology comparison for SS+FW combination

According to the results obtained from the simulations, as shown in Figure 4, similar purification efficiency can be achieved in both biogas upgrading technologies (>98 %) with the difference in the height of transfer unit

(HTU) and the number of transfer unit (NTU) required. The overall HTU required in the absorber to achieve high CH_4 purity using water scrubbing technology is higher than the chemical scrubbing technology. The water absorber records result at 5.03m, while the chemical scrubber achieves 0.324 m. Contrarily, the NTU required in the chemical absorber records a higher range at 102.667 m while 7.334 m in the water absorber. The low HTU required in chemical scrubbing results from the higher solubility of targeted components in the solvent and the higher solvent flow rate into the absorber than in the water scrubber. In addition, the chemical scrubber is designed based on the packed column design for high solvent and gas flow rates. As for the water scrubber, the HTU required is higher due to the lower flow rate of solvent, and the NTU required is lower due to the higher packing factor and surface area of packing used in the equipment. The water stripper used in chemical scrubbing technology achieves 5.056 m HTU and 6.926 NTU, whereas the air stripper applied in water scrubbing technology records 3.905 m HTU and 5.44 NTU. With similar theories, the HTU of a separation column can be affected by the packing parameters and flow rate of solute in solvent, as stated earlier. It can be concluded that the HTU and NTU have an inversely proportional relationship. The higher the HTU, the lower the NTU and these result trends meet the basic phenomena in separation column and mass transfer (Vo et al., 2018).

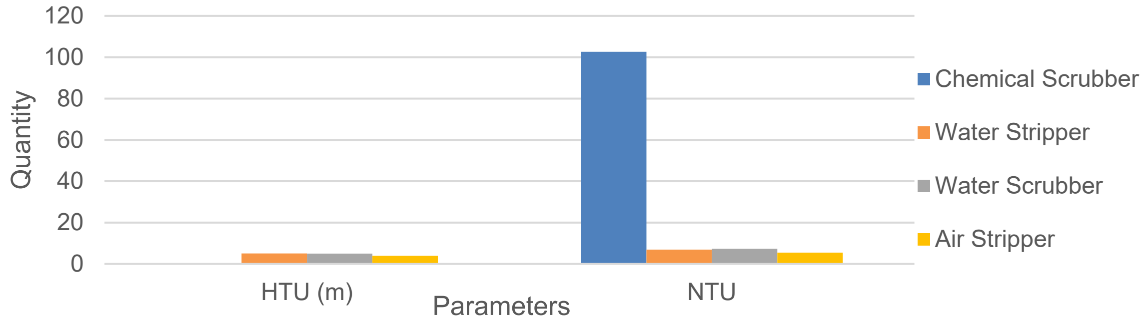

Figure 4: Comparison between chemical and water scrubbing technologies for biogas upgrading

3.4 Impact of HRT

A few parameters need to be set at constant to prevent the interruption of the targeted variable to determine the effect of HRT. Since the ACoD model is selected, the parameters to be fixed in this investigation will be the feed ratio and the operating conditions of the equipment, such as anaerobic digester and biogas upgrading technologies. The operating condition for the anaerobic digester has remained at mesophilic conditions. At the same time, the absorber and stripper for chemical and water scrubbing technologies are set in the same manner as mentioned in Section 2. The HRTs are set at 5 to 30 d. The cumulative biogas production shows a directly proportional relationship based on the results. In the ACoD of FW and SS, the cumulative biogas production in the anaerobic digester increases from 1,204.1 kg/batch (5 d), 1,619.84 kg/batch (10 d), 2,112.7 kg/batch (15 d), 2,630.5 kg/batch (20 d), 3,162.2 kg/batch (25 d) and 3702.9 kg/batch (30 d). As the HRT increases, the substrate is retained in the anaerobic digester for a longer time; thus, the core microorganisms present in the AD process will perform their tasks at every stage continuously, synthesising biogas gradually until the depletion of nutrients and a higher degree of inhibitions occur. It is also observable that the methane composition in both cases experienced an up-and-down trend, with the highest methane content achieved at 10 d of HRT, as shown in Figure 5. The rising slopes indicate that the methanogens efficiently utilise the carbon dioxide produced from the previous stages to produce methane until the optimal HRT is 10 d. When the HRT extends, the digestion process continues at every stage, and the CO_2 gas accumulates in the anaerobic digester, besides CH_4 gas and other trace elements. Since the rate of consumption of CO_2 is lower than the rate of generation of CH_4, the CO_2 content in the biogas increases gradually with the constantly decreasing CH_4 composition.

3.5 Impact of feed ratio

In the feed ratio analysis, similar ACoD models are used in the HRT analysis. The portion of the co-substrate FW is maintained at one while changing the portion of SS from 1 to 5. The overall operating conditions for all equipment are akin to those mentioned in the HRT analysis except for the HRT, which sets at 30 d. The overall trend shows a proportional relationship between biogas and methane production based on the results obtained, as shown in Figure 6. In the FW + SS group, the cumulative biogas production increases from 2,045.72 kg/batch, 3,702.91 kg/batch, 5,353.96 kg/batch, 6,528.65 kg/batch and 6,935.12 kg/batch for SS-to-FW ratio of 1:1, 2:1, 3:1, 4:1 and 5:1. On the other hand, the methane composition decreases as a higher portion of SS is mixed with the FW, representing an inversely proportional relationship. This is because the increase in the SS amount only results in a significant rise in moisture content and a few vital elements in the mixed feedstock. Hence, the primary sources of essential nutrients remain the same: the co-substrate like FW. By observing the chemical compositions of the co-substrate, the primary component that contributes the most to the formation of CO_2, carbohydrates and celluloses possess the highest percentage among the components in FW. Thus, the rate of generation of CO_2 is higher than the rate of consumption to produce CH_4 in FW, resulting in the higher accumulation of CO_2 at the 30 d HRT and lower CH_4 content.

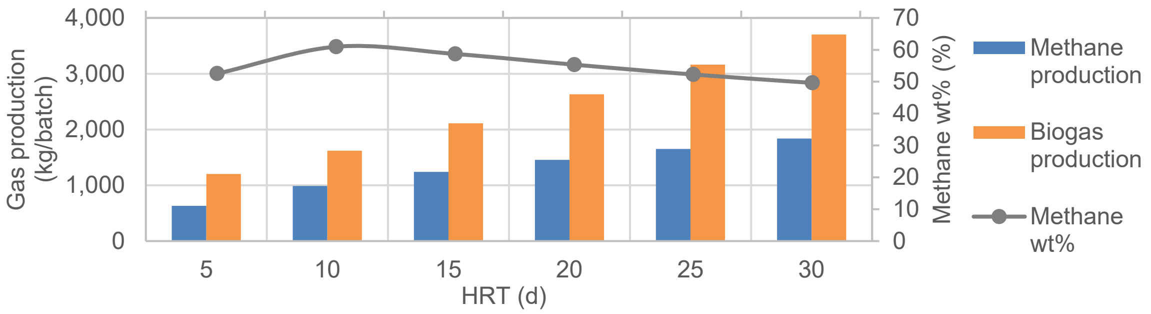

Figure 5: Impacts of HRTs on the biogas production for AD with FW+SS feedstock

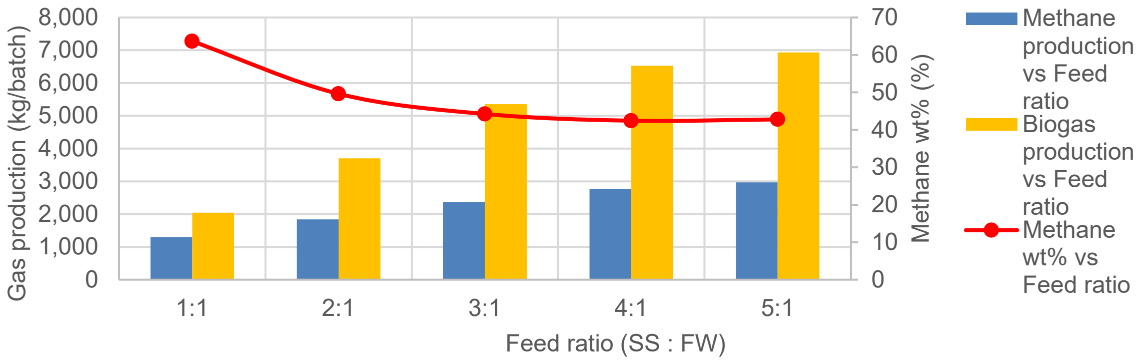

Figure 6: Effect of different Feed Ratios for FW + SS combination

4. Conclusions

The investigation on the optimisation for the AD of SS is executed successfully through the implementation of biogas upgrading technologies and ACoD with other available feedstocks such as CS, FW, CM POME. This study develops several AD and ACoD models with biogas upgrading technologies using the Superpro simulation software. The first research objective is achieved as the AD models of SS with chemical and water scrubbing technologies are developed successfully, with validated results based on the AD behaviour. Then, another research objective is accomplished with the introduction of ACoD with other feedstocks and investigations on the effects of feed ratio and HRT. All the models developed operate smoothly and are validated successfully. In conclusion, the AD of SS can be optimised by introducing various feedstocks such as CS, FW, CM and POME with higher nutrient compositions. Among these feedstocks, FW is the best co-substrates synthesising the highest methane purity in biogas, considering the desired criteria in the HRT and feed ratio analysis. By comparing the ACoD models, the FW+SS set scores a higher AD performance than the others, as the methane purity obtained by the combination in the analysis is 49.62 % which is the highest among the co-substrates. Although the overall biogas production in ACoD of SS with CS is higher than the FW as co-substrate, the low methane purity indicates that the impurities in the biogas produced will be enormous, indicating higher operating costs in the biogas upgrading technologies. For the chemical scrubbing technology, the best HRT and feed ratio for the combination of FW with SS are 30 d (feed ratio of 1:2) and 1:5 (30 d HRT), by considering the amount of biogas and CH_4 produced. If the methane purity is considered, ten days HRT (feed ratio of 1:2) and 1:1 ratio (30 d HRT) are preferred, with the highest methane content in biogas.

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