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Anaerobic Co-Digestion of Food Waste with Sewage Sludge: Simulation and Optimization for Maximum Biogas Production

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Abstract: Anaerobic co-digestion (ACD), where two or more substrates are digested simultaneously, is able to prevent the problems associated with mono-digestion. The aim of this study is to develop a simulation model of ACD of food waste (FW) with sewage sludge (SS) for biogas production coupled with pre-treatment, sludge handling and biogas upgrading using SuperPro Designer v9.0. The Design Expert v13 is employed to perform optimization and evaluate the effect of hydraulic retention time (HRT), sludge recycle ratio, water to feed ratio (kg/kg) and SS to FW ratio (kg/kg) on the methane flow, chemical oxygen demand (COD) and volatile solids (VS). The results show that the methane yield of 0.29 L CH_4/g COD removed, COD removal efficiency of 81.5% and VS removal efficiency of 69.2% are obtained with a HRT of 38.8 days, water to feed ratio (kg/kg) of 0.048, sludge recycle ratio of 0.438 and SS to FW ratio (kg/kg) of 0.044. Economic analysis has shown this study is feasible with a payback time of 6.2 years, net present value (NPV) of $5,283,000 and internal return rate (IRR) of 10.2%. This indicates that the ACD of FW and SS is economically feasible in a larger scale.

Keywords: anaerobic digestion; food waste; sewage sludge; methane yield; biogas

1. Introduction

The amount of food waste (FW) produced globally has increased vastly due to the growth in population and urbanization [1]. Pramanik et al. [2] outlined the statistics of Solid Waste Corporation Management of Malaysia (SWCorp) that 16,687 tons of food waste is produced daily in Malaysia. The development of the National Strategic Plan for Food Waste Management by the Malaysian government is to encourage the diversion and minimization of food waste into landfill by processing food waste to compost; the proper treatment of food waste and effective recovery of landfill gases [3,4]. Additionally, the COVID-19 virus outbreak caused the implementation of lockdown in different countries, resulting in the movement of workers being restricted, which caused the generation of food waste at the production level, since the crops were not harvested on time [5].

According to Lim et al. [6], the worldwide energy demand for 2030 is estimated to rise from current total of 472 quadrillion Btu to 678 quadrillion Btu. Therefore, this huge demand has caused an urgent need to replace the fossil fuel with alternative energy technologies such as biomass, wind and solar. Among all the renewable energy, biomass is one of the dominant energies used globally which can deliver a huge reduction in carbon emissions. Briquetting, gasification and anaerobic digestion are all possibilities, which transform the raw biomass into fuel products such as biogas [7]. Biogas is comprised of 60–70% methane, 30–40% carbon dioxide and trace amounts of hydrogen, hydrogen sulfide and ammonia [8]. Biogas can be used in the generation of heat and electricity and also as biofuel to replace the non-renewable fossil fuel [9]. Biogas can be produced using different biodegradable wastes such as food waste, animal manure, forest and agriculture waste [10].

Anaerobic digestion (AD) is proposed as a low-cost and environmental friendly technology for renewable energy production as compared with landfill, incinerations and composting process [8,11]. The remaining digestate is turn into a nutrient rich sludge which can be sold as fertilizer [8,12]. Anaerobic co-digestion (ACD) of FW with other substrates is proposed to compensate for the problems occurring in the mono-digestion of food waste. ACD is used widely in most of the industry to prevent the low buffer capacity and the high carbon to nitrogen ratio (C/N) problem associated with the mono-digestion of FW [13]. Mehariya et al. [14] reported that one of the best co-substrates for FW digestion is sewage sludge (SS). SS is rich in nitrogen and trace components but low in biodegradable organic content, therefore mono-digestion of SS results in low biomethane potential [15]. SS is one of the potential co-substrates in the ACD of FW as it is able to provide alkalinity and essential micronutrients in the digestion process to improve the acidization in the AD of FW [16]. SS has high amounts of active bacteria which make the co-substrate favorable to the formation of microorganisms in the AD process [13]. Moreover, the low carbon to nitrogen (C/N) ratio of 6–10 in the SS needs to be co-digested with substrates that have higher C/N ratio such as FW to compensate for the lack in organic substances and prevent any inhibition in the process. This is due to the fact that an optimal C/N ratio for the anaerobic digestion is in the range of 20-30 [17]. Thus, the ACD of these two substrates is an attractive approach in increasing the methane yield. Table 1 displays the composition of FW and SS.

Table 1. Kitchen food waste and sewage sludge composition [18,19].

Component	Composition (%)	
	Food Waste	Sewage Sludge
Moisture	80.3	83.8
Total solids	19.7	12.4
Ash	1.9	3.8
Volatile solids	18.8	9.7
Carbohydrates	59.8	3.3
Protein	21.8	33.4
Lipids	15.7	6.6

The AD process can be influenced by several operating parameters such as the substrates' composition, the mixing ratio of co-substrate, types of reactor as well as the environmental factors like temperature, hydraulic retention time (HRT), organic loading rate (OLR), pH and nutrients [20]. HRT is known as the average time needed for the liquid organic matter to spend in the digester [21]. Short retention time results in insufficient time for optimal substrate degradation process while prolonged retention time requires a large volume of reactor although the methane yield is higher [9]. According to Tyagi et al. [22], the optimum HRT for mesophilic digestion is 10–40 days whereas thermophilic digestion is 14 days. Besides that, the moisture content is one of the significant factors that affects the AD process. The methanogenic activity in high-solids sludge digestion increases when the initial moisture content increases from 90 to 96% in the AD of organic municipal solid waste under mesophilic conditions [23]. Nevertheless, lower volatile solids are reported in the substrate when the initial moisture content is higher as the re-addition of water into the digesters would cause the wash out of nutrients from microorganisms [23]. The ratio of sludge recycle significantly affects the AD performance. According to Jiang et al. [24], biogas yields increase from 0.17 to 4.03 L/(L.d) when the OLR increases from 0.75 to 9.00 g VS/(L.d) for AD of municipal solid waste. However, the biogas yield decreased to 3.8 L/(L.d) when OLR increased to 11 g VS/(L.d). This is because overfeeding organic solids into the anaerobic digester will cause the accumulation of VFAs and making the environment become less favorable for the micro bacteria to survive due to the decrease in pH level [13]. Different mixture ratios of the food waste and sewage sludge could affect the digestion performance as the ratio implies the nutrient balance in the mixture [17]. Chow et al. [17] reported that the optimum mixing ratio for the ACD of FW and SS is at a 60:40 ratio.

In order to predict the actual scenarios that happen in an AD process by using the minimum amount of time and resources, simulation work is preferred over the experimental work. Aguilar et al. [25] has carried out a study to investigate the feasibility of ACD of FW and primary sludge under the thermophilic and mesophilic conditions using ASPEN PLUS. However, the study is mainly focused on the power generation and heat recovery process. Thus, the main purpose of this paper is to develop the simulation model to determine the feasibility of the biogas generation from the ACD of FW with SS and examining the effect of HRT, water to feed ratio (kg/kg), sludge recycle ratio and SS to FW ratio (kg/kg) on the methane flow, chemical oxygen demand (COD) and volatile solids (VS) removal efficiencies. The process includes the pre-treatment of substrates, AD process, and followed by biogas upgrading and sludge treatment. The simulation and optimization are modelled with SuperPro Designer v9.0 and Design Expert v13. Based on the results, the methane yield (L CH4/kg $COD_{removed}$) is calculated and compared with the literature values. Lastly, economic analysis is conducted to determine the feasibility of this study.

2. Materials and Methods

2.1. SuperPro Simulation Model for Anaerobic Co-Digestion of Food Waste and Sewage Sludge

The ACD process of FW and SS for biogas production is modelled using the SuperPro Designer v9.0. The simulation flowsheet for the anaerobic ACD of FW and SS is shown in Figure 1. The feed flowrate of 25,000 kg/h is used as the basis of this simulation work, as this is according to the statistics of food waste generated in Petaling Jaya one week before the implementation of the Movement Control Order (MCO) by the Malaysia government [26]. The FW and SS with a total flowrate of 25,000 kg/h were first mixed together and sent to the grinder (GR-101) and sterilizer (ST-101) for mechanical and thermal pre-treatment. The mass flowrate and composition of the two substrates used in the SuperPro simulations are shown in Table A1 (Appendix A). Pre-treatment needs to be employed in the digestion process to accelerate the hydrolysis rate for proteins and lipids and enhance the biogas productions, especially for the digestion process involving food waste due to presence of cellulose content [27]. According to Izumi et al. [28], when the mean particle size of substrates reduced from 0.843 mm to 0.391 mm, the total COD solubilization increase by 40%. Therefore, mechanical pre-treatment such as grinding need to be employed to increase the surface area for a better contact between the substrate itself and the bacteria [13]. Furthermore, thermal pretreatment is required to destroy the cytomembrane of substrate and thus accelerate the hydrolysis reactions and biogas yield [29]. Ma et al. [30] found out that the biogas production from FW is improved by 11% when the substrates undergoes heat treatment at 120 °C for 30 min. The increase in biogas yield by thermal pretreatment is due to the COD solubilization.

The pretreated substrates (Mixtures-2) are then mixed with water and sent to the anaerobic digester (AD-101) for biogas production. The digester is maintained at a temperature pf 35 °C for mesophilic conditions [31]. The biogas produced from the top of the anaerobic digester is sent to a bio trickling filter (TF-101) and a condenser (HX-101) for desulfurization and dehumidification for biogas upgrading purposes. The biogas upgrading process is significant to prevent the formation of carbonic acid and sulfuric acid due to the presence of hydrogen sulfide (H_2S) and water (H_2O) that increase the corrosion rate in the gas engine [32]. Acid is formed when the water reacts with H_2S. As reported by Khoshnevisan et al. [33], the permissible H_2S concentration in the biogas used for direct combustion purpose is 200–500 ppm. A biological approach such as bio trickling filtration (BTF) is employed in the desulfurization process due to its low operating condition (30–35 °C and 1 atm) [34]. The bio trickling filter bed is packed with sulfide-oxidizing bacteria (SOB) which H_2S oxidized on the bed material [33]. According to Huertas et al. [35], the H_2S removal efficiency using BTF system can be more than 95%. The biogas is saturated with water vapor which may cause condensation and reduce the combustion performance [36]. Biogas with relative humidity less than 80% is required for the high effectiveness of the gas engine [37]. The upgraded biogas can then be used as biofuel in a gas engine.

The digestate produced from the bottom is sent for aerobic digestion in the aerobic pond (AB-101) to further digest the organic matters under an oxygen-rich environment. High removal of biochemical oxygen demand (BOD) can be achieved in the aerobic pond. Stoichiometry reactions of Equations (1) and (2) show the conversion of the organic matter which is carried out by the mixed bacterial cultures [38]. According to Butler et al. [39], the typical detention time for an aerobic pond is 2–6 days and with a BOD removal efficiency of 95%. The kinetics adopted in the anaerobic and aerobic digestion are shown in Table 2. Monod kinetics models are used in this study.

$$\text{Organic matter} + O_2 + \text{nutrients} \overset{\text{bacteria}}{\rightarrow} CO_2 + NH_3 + \text{new cells} \tag{1}$$

$$\text{Cells} + 5O_2 \overset{\text{bacteria}}{\rightarrow} 5CO_2 + 2H_2O + NH_3 + \text{energy} \tag{2}$$

Table 2. Kinetics' parameters for anaerobic and aerobic digestion.

Parameter	μ_{Max} (1/h)	K_s (mg/L)	Source
Anaerobic digestion			
Carbohydrates	0.052	465	[40]
Protein	0.033	465	[40]
Lipids	0.029	465	[40]
Aerobic digestion	0.126	21.23	[41]

Primary and secondary clarifiers (CL-101 & CL-102) are used before and after the aerobic pond as a waste-activated sludge treatment and act as the holding tank. The sludge leaving from the bottom of the aerobic pond is recycled back to the aerobic pond feed inlet. The recycled sludge is known as return activated sludge (RAS) [38]. Coagulant is added into the secondary clarifier to improve the performance of suspended solid removal. To ensure the wastewater meets the discharge effluent standards (Standard A), the granular media (GM) filter (GMF-101) is used to reduce the BOD to <20 mg/L and COD < 120 mg/L [42]. The sludge that leaves from the bottom of CL-101 is sent to a splitter (FSP-101) where a portion of it is recycled back to the AD-101 inlet and the remainder is mixed with the CL-102 sludge, prior to being sent to the belt press filter (BF-101) for dewatering process. Finally, the dewatered sludge is sent for drying in the sludge dryer (SLDR-101) before being sold as fertilizer.

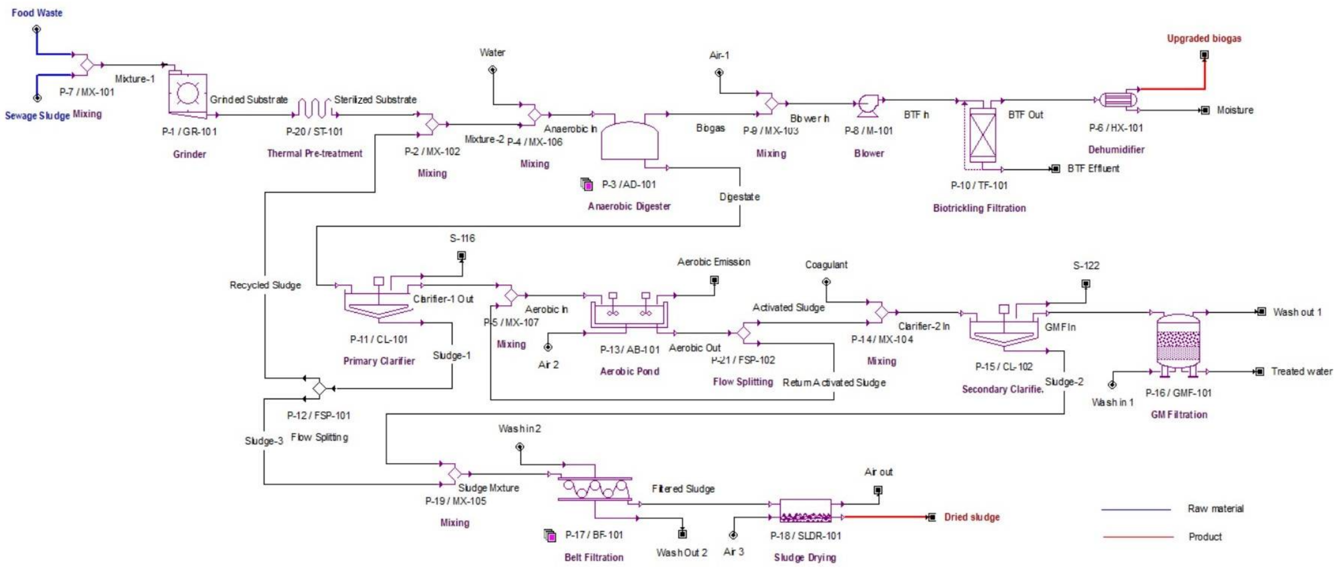


Figure 1. Simulation flowsheet for anaerobic co-digestion of food waste with sewage sludge.

The HRT used in the anaerobic digester, CL-101 sludge recycle ratio, the amount of water required to be added into the process and the amount of SS and FW in the feedstock is optimized in the subsequent stage. The base case simulations use 10 days of HRT and zero amount of water, recycled sludge and sewage sludge. The base case results are shown in Section 3.5 and compared with the optimized results. The specifications used in the process for each equipment is summarized in Table A2.

2.2. Process Optimisation

In this study, the optimum HRT, water to feed ratio (kg/kg), sludge recycle ratio and the SS to FW ratio (kg/kg) is determined using Design Expert v13 to give maximum methane flow, COD and VS removal efficiencies at the anaerobic digester. Response surface methodology (RSM) is employed. RSM is an optimization tool that involves complex calculation which can be used to analyze the interrelationship between the process variables and their influence on the process performance and quality [43,44]. In this study, optimization is conducted through the application of RSM uses the Box–Behnken Design (BBD) method to determine the number of experiments. Analysis of Variance (ANOVA) to test the adequacy of the derived model and the significance of each of the process parameters on the response are discussed in Section 3. The model equation is derived using RSM which can be applied for the response estimation and determination of optimal conditions [38,39]. Table 3 shows the independent variables set in the Design Expert and their upper and lower bounds limits which are chosen based on the literature values [12]. The responses variables include methane yield (L CH_4/g COD removed), COD removal efficiency (%) and VS removal efficiency.

Table 3. Upper and lower bound limits of the independent variables.

Independent Variables	Annotation	Unit	Lower Bound	Upper Bound
HRT	A	days	10	40
Water to feed ratio	B	-	0	1
Sludge recycle ratio	C	-	0	1
Sewage sludge to food waste ratio	D	-	0	1

There was a total of 29-run of BBD design points generated from the Design Expert v13 which includes 24 factorial experiments and 5 repeated runs at the center point (Table 3). The design matrix is shown in Table A3. The data for different experiments are entered into the SuperPro simulation manually and the results of methane flow (kg/h), COD and VS removal efficiencies are attained. The results for different trials are then analyzed using Design Expert. The effects of alteration of the process parameters and their impacts on the response variable are discussed. Subsequently, the methane yield is calculated using Equation (3) based on the methane flow and COD removal efficiency obtained from the simulations.

$$\text{Methane Yield } (\text{L CH}_4/\text{g COD removed}) = \frac{Q_{CH_4}}{Q_{in}(COD_{in} \times \text{COD Removal Efficiency})} \quad (3)$$

where Q_{CH4} is the methane volumetric flowrate (L/h), Q_{in} is the feedstock volumetric flowrate (L/h), COD_{in} is the initial COD concentration (g/L). The methane mass flow obtained from the simulations is converted into volumetric flowrate using density of methane (0.627 kg/m^3) at 35 °C.

3. Results and Discussions

In this section, the effect of the HRT, water to feed ratio, sludge recycle ratio and SS to FW mixing ratio on methane flow, COD and VS removal efficiencies based on the results from RSM are discussed. The ANOVA analysis and three-dimensional plot of the response surface are displayed to see the interactions between the process parameters. For all the responses, the experimental results were fitted to the second order regression polynomial equation. Subsequently, numerical optimization results which give the optimal conditions are shown. These optimum process parameters were used in the SuperPro simulations and the generated final results are discussed and compared with the base case results. Lastly, the results of economic analysis are summarized.

3.1. Effect of HRT, Water to Feed Ratio (kg/kg), Sludge Recycle Ratio and the SS to FW Ratio (kg/kg) on Methane Flow

Methane is the main product in the ACD process as it represents the performance of the entire digestion process as well as the economic feasibility. Therefore, the effect of the process parameters on the methane production needs to be studied. The ANOVA analysis for the response surface of methane flow is displayed in Table 4.

Table 4. ANOVA analysis for methane flow response.

Source	df	Sum of Squares	Mean Squares	F-Value	*p*-Value	
Model	14	1.17×10^6	83,277.40	18,008.96	<0.0001	Significant
A-HRT	1	3.07×10^5	3.07×10^5	66,292.88	<0.0001	Significant
B-Water to Feed Ratio	1	74,351.11		16,078.63	<0.0001	Significant
C-Sludge Recycle Ratio	1	21,333.09		4613.34	<0.0001	Significant
D- SS to FW Ratio	1	4.36×10^5		94,185.27	<0.0001	Significant
AB	1	5.76		1.25	0.2904	
AC	1	78.73		17.03	0.0021	
AD	1	860.51		186.09	<0.0001	
BC	1	75.86		16.40	0.0023	
BD	1	1.21		0.2617	0.6201	
CD	1	112.34		24.29	0.0006	
A^2	1	89,639.28		19,384.74	<0.0001	
B^2	1	441.80		95.54	<0.0001	
C^2	1	0.8471		0.1832	0.6777	
D^2	1	2134.19		461.52	<0.0001	

Models with *p*-value less than 0.05 are significant. From Table 4, it can be seen that the *p*-value for A, B, C, D, AC, AD, BC, CD, A^2, B^2 and D^2 are less than 0.05. This concludes that these model terms significantly impact the methane flow. Conversely, for the model with *p*-value larger than 0.05, this indicates that the term is not significant. By examining the fit summary, it showed that the quadratic model is the best fit for the response. The second order polynomial model Equation (4) gives the relationship between the HRT, water to feed ratio, sludge recycle ratio and SS to FW ratio from the experimental data and can be used as an estimation for the methane flow.

$$\begin{aligned}\text{Methane flow} = {} & 661.78 + 44.94A - 224.65B + 118.49C - 565.31D + 0.21AB - 0.97AC \\ & + 1.96AD + 17.42BC - 2.20*D + 27.86CD - 0.61A^{2} + 36.99B^{2} - 1.78C^{2} \\ & + 78.86D^{2}\end{aligned} \quad (4)$$

The perturbation plot shown in Figure 2 is used to monitor the change in the methane flow by changing one of the process parameters throughout its range whereas the other variables are kept constant. From Figure 2, it can be noticed that the change in HRT results in a larger deviation from the reference point compared to the other three ratios. This shows that HRT is the most sensitive parameter in methane flow response, a slight change in HRT results in large changes in the methane flow.

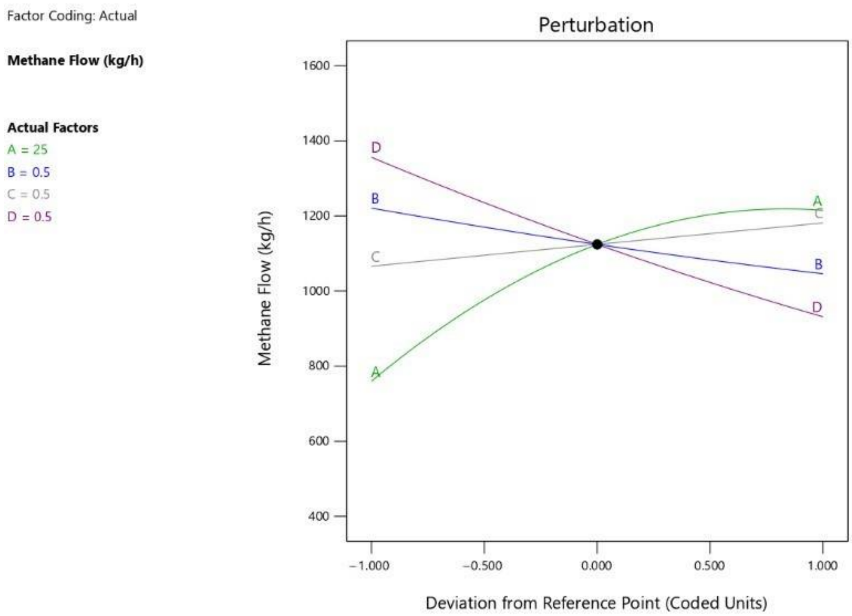


Figure 2. Perturbation plot of methane flow response.

Figure 3 show the 3D surface graph plot of the significant models with a *p*-value of less than 0.05 in the ANOVA analysis. As shown in Figure 3a, methane flow increases when the HRT and sludge recycle ratio increases. Maximum methane mass flowrate is achieved when the HRT is at 40 days and the sludge from primary clarifier is fully recycled back to the anaerobic digester. The HRT must be long enough to avoid the methanogens being washed out from the digester and causing the process failure [45]. Long HRT promotes higher microorganism activity and higher biogas yield but excess HRT could lead to ammonic nitrogen accumulation and inhibition to anaerobic digestion [46,47]. According to Tyagi et al. [22], the optimum HRT for mesophilic digestion is 10–40 days. Figure 3a plot shows that the methane flow increased linearly with the HRT, and indicates that the response is in line with the optimum range.

Meanwhile, in order to enhance the methane production, the amount of sludge recycled needs to be high. This is because the organic matters in the anaerobic digester inlet increases, thus leading to more methane being produced. Magdalena et al. [48] reported that the anaerobic inhibition may occur if the feeding volume to the digester is too high, which results in shock loading of microorganisms and accumulation of VFA. However, the linear relationship between the sludge recycled ratio and methane flow throughout the entire range indicates that the simulated digester volume is capable of handling all the sludge leaving from the bottom of CL-101. From Figure 3b, the methane flow decreases along with the SS amount due to the amount of nutrients and production of VFA is not taken into account in the SuperPro simulations. For Figure 3c, it can be noticed that when more water is added into the AD process, lesser methane is produced. The results deviate from the literature findings where an increase in moisture content enhances the methane production. One of the reasons may be due to the decrease in the composition of organic contents.

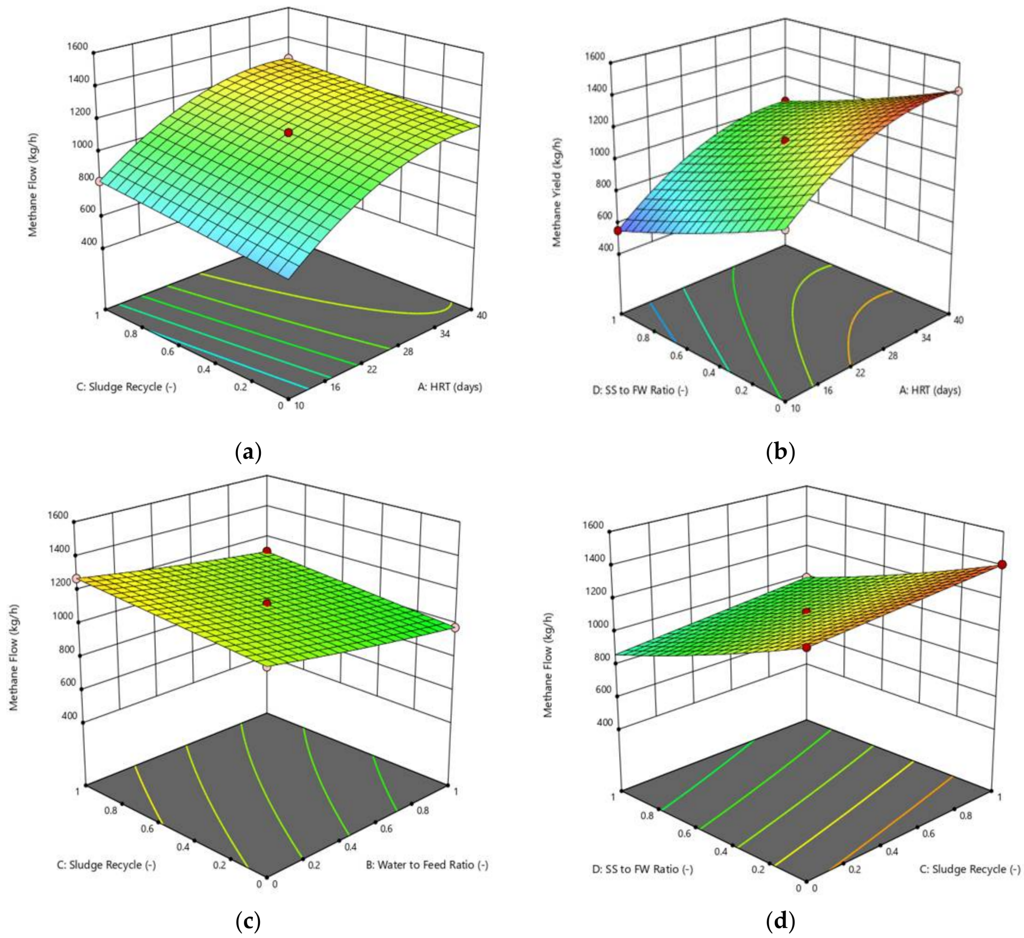


Figure 3. 3D surface graph plot for methane flow as a function of (**a**) HRT and sludge recycle ratio; (**b**) HRT and SS to FW ratio; (**c**) water to feed ratio and sludge recycle ratio; (**d**) sludge recycle ratio and SS to FW ratio.

3.2. Effect of HRT, Water to Feed Ratio (kg/kg), Sludge Recycle Ratio and the SS to FW Ratio (kg/kg) on Chemical Oxygen Demand (COD) Removal Efficiency

COD is a measurement of oxygen needed to oxidize the organic matter in water [49]. COD is one of the important characteristics in the digested sludge that is used for land application, as the COD levels need to comply with the local environmental standards [50]. Therefore, the COD concentration in the inlet and outlet need to be recorded and removal efficiency is calculated using Equation (5) [51]. The ANOVA analysis for the response surface of COD removal efficiency is displayed in Table 5.

$$\text{COD Removal Efficiency}(\%) = \frac{\text{Initial COD} - \text{Final COD}}{\text{Initial COD}} \times 100\ \% \quad (5)$$

Table 5. ANOVA analysis for COD removal efficiency response.

Source	Sum of Squares	Mean Squares	F-Value	*p*-Value	
Model	602.82	43.06	143.38	<0.0001	Significant
A-HRT	314.14	314.14	1046.07	<0.0001	Significant
B-Water to Feed Ratio	20.15	20.15	67.11	<0.0001	Significant
C-Sludge Recycle Ratio	17.44	17.44	58.07	<0.0001	Significant
D-SS to FW Ratio	163.77	163.77	545.33	<0.0001	Significant
AB	0.9708	0.9708	3.23	0.0974	
AC	2.91	2.91	9.68	0.0090	
AD	10.05	10.05	33.47	<0.0001	
BC	0.1226	0.1226	0.4083	0.5348	
BD	0.7206	0.7206	2.40	0.1473	
CD	3.47	3.47	11.54	0.0053	
A^2	69.52	69.52	231.49	<0.0001	
B^2	0.3212	0.3212	1.07	0.3214	
C^2	2.82	2.82	9.41	0.0098	
D^2	2.88	2.88	9.58	0.0093	

The model terms of A; B; C; D; AC; AD; CD; A^2; $C^{2;}$ and D^2 are significant as the *p*-value is less than 0.05. This shows the COD removal efficiency is significantly affected by these model terms. Meanwhile, since AB; BC; BD; and B^2 have a *p*-value larger than 0.05, therefore it can be said that these terms are not significant. The fit summary results generated from Design Expert shows that the response surface can be modelled using quadratic model. The second order polynomial model Equation (6) is used to estimate the value of COD removal efficiency.

$$\text{COD removal efficiency} = 62.53 + 1.16A + 3.45B + 1.70C - 12.58D - 0.08AB - 011AC + 0.21AD - 0.70BC + 1.70BD + 3.72CD - 0.02A^2 + 0.97B^2 - 2.78C^2 - 2.80D^2 \quad (6)$$

The perturbation plot for the COD removal efficiency response surface is shown in Figure 4. Similar to the perturbation plot for methane flow in Figure 2, the HRT gives the largest deviation in COD removal efficiency, indicating it is the most sensitive parameter.

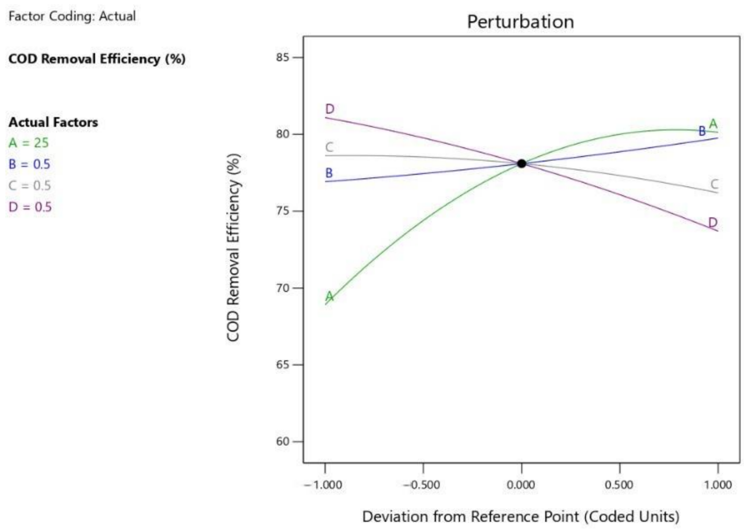


Figure 4. Perturbation plots for COD removal efficiency response.

Figure 5 displays the 3D surface plot for the COD removal efficiency response surface. The model terms shown in Figure 5a–c give significant results in ANOVA analysis. Even though the model terms in Figure 5d are insignificant, however it is shown to give the effect of the addition of water in the ACD process to the COD removal efficiency. From Figure 5a, it can be noticed that COD removal efficiency increased along with the HRT at constant sludge recycle ratio. This is because as the HRT increases, the methane production increases, conversion of carbon element to biogas is higher therefore the COD removal efficiency is higher [51]. This can also be used to explain Figure 5b where the COD removal efficiency is maximum at zero SS to FW ratio. However, the COD removal efficiency decreases when the sludge recycle ratio increases and the methane flow increases. This is due to the fact that, as the sludge is recycled, the amount of organic matter that contributes to the COD value in the anaerobic digester inlet stream increases. Therefore, with the same amount of organic matter being degraded as compared to zero recycle, the COD removal efficiency decreases. It can be noticed that the 3D surface plot in Figure 5c is flat which indicates that these two process parameters have a minimal effect on COD removal efficiency. From Figure 5d, the COD removal efficiency increases when the water to feed ratio increases from 0 to 1. This is due to the fact that the addition of water causes the COD concentration in the feed to be reduced.

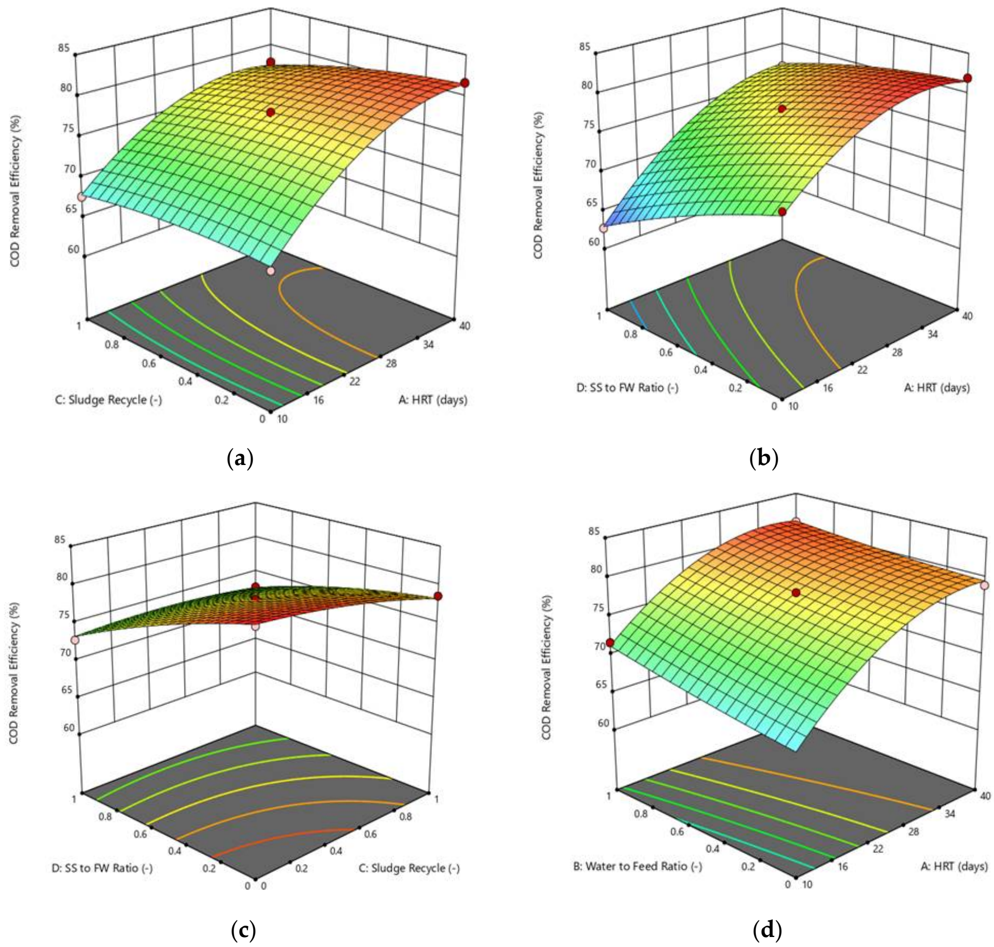


Figure 5. 3D surface graph plot for COD removal efficiency as a function of (**a**) HRT and sludge recycle ratio; (**b**) HRT and SS to FW Ratio; (**c**) sludge recycle ratio and SS to FW ratio; (**d**) HRT and water to feed ratio.

3.3. Effect of HRT, Water to Feed Ratio (kg/kg), Sludge Recycle Ratio and the SS to FW Ratio (kg/kg) on Volatile Solids (VS) Removal Efficiency

Volatile solids (VS) is part of the total solids in the substrate [51]. VS represents the metabolic status of the microbial community in anaerobic system [50]. Equation (7) is used to calculate VS removal efficiency. The VS removal efficiency is known as the amount of volatile solids decomposed divided by the quantity of volatile solids being fed into the anaerobic digester [52]. Table 6 shows the ANOVA analysis for the VS removal efficiency response surface.

$$\text{VS Removal Efficiency}(\%) = \frac{\text{Initial VS} - \text{Final VS}}{\text{Initial VS}} \times 100\ \% \quad (7)$$

Table 6. ANOVA analysis for VS removal efficiency response.

Source	Sum of Squares	Mean Squares	F-Value	*p*-Value	
Model	469.64	33.55	338.62	<0.0001	Significant
A-HRT	191.64	191.64	1934.49	<0.0001	Significant
B-Water to Feed Ratio	109.60	109.60	1106.30	<0.0001	Significant
C-Sludge Recycle Ratio	9.14	9.14	92.27	<0.0001	Significant
D- SS to FW Ratio	113.95	113.95	1150.25	<0.0001	Significant
AB	1.22	1.22	12.33	0.0043	
AC	0.7887	0.7887	7.96	0.0154	
AD	5.77	5.77	58.26	<0.0001	
BC	1.24	1.24	12.50	0.0041	
BD	2.19	2.19	22.13	0.0005	
CD	0.6744	0.6744	6.81	0.0228	
A2	41.28	41.28	416.72	<0.0001	
B2	0.0525	0.0525	0.5298	0.4807	
C2	0.5517	0.5517	5.57	0.0361	
D2	1.12	1.12	11.26	0.0057	

From Table 6, it can be noticed that the *p*-value for all the model terms are less than 0.05, except for B^2. This indicates that only B^2 is not significant. The VS removal efficiency response surface can be modelled using a quadratic model based on the fit summary results using Equation (8).

$$\begin{aligned}\text{VS Removal Efficiency} \\ &= 53.53 + 0.89A + 9.01B + 0.89C - 11.52D - 0.09AB - 0.06AC + 0.16AD - 2.23BC \\ &+ 2.96BD + 2.09CD - 0.01A^2 - 0.39B^2 - 1.26C^2 - 1.79D^2\end{aligned} \quad (8)$$

Figure 6 shows the perturbation graph for the VS removal efficiency response surface. Unlike the methane flow and COD removal efficiency, both the HRT and water to feed ratio have the dominant effect on the VS removal efficiency. Reason of this is discussed under the description for Figure 7.

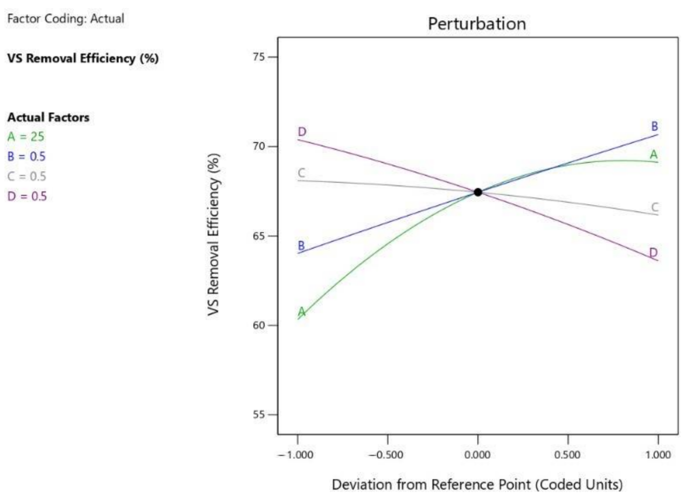
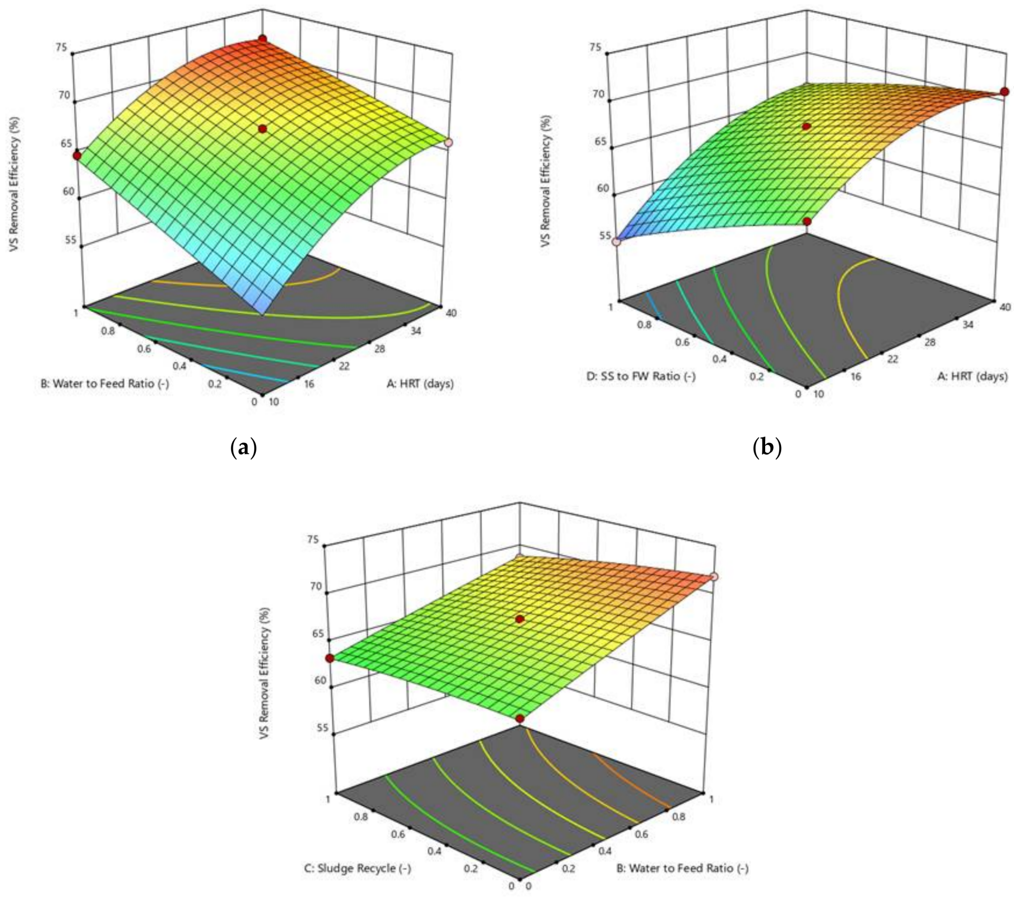


Figure 6. Perturbation plots for VS removal efficiency response.



(**a**) (**b**) (**c**)

Figure 7. 3D surface graph plot for VS removal efficiency as a function of (**a**) HRT and water to feed ratio; (**b**) HRT and SS to FW ratio; (**c**) water to feed ratio and sludge recycle ratio.

Three of the model terms' 3D plots are shown in Figure 7 to discuss the effect and interactions of each process' parameters on the VS removal efficiency. Based on the ANOVA analysis in Table 6, all the model terms which involved two independent variables are significant. The curvature of the plot shown in Figure 7a is the largest. This indicates that both the HRT and water to feed ratio has a linear relationship and have a significant impact on the removal of VS. Hence, the maximum VS removal efficiency of 72.5% can be achieved using the longest HRT (40 days) and highest amount of water (25,000 kg/h). Lower VS is present in the digester and is reported when the moisture content is high, due to the possibility of the washing out of organic solids when water is added into the anaerobic digestion process [23]. The poorer VS present indicates a higher VS removal efficiency. Therefore, this explains the perturbation plot in Figure 6 which shows that the water to feed ratio has a significant effect on the VS removal rate. Furthermore, the VS concentration indicates the potential amount of biogas that can be produced from the substrates [51]. Hence, the longer the HRT, the higher the methane yield, the higher the VS removal efficiency. In Figure 7b, the VS removal efficiency decreases when the amount of SS increases. This is due to that fact that less biogas is produced when the amount of sewage sludge increases. Moreover, it can be seen from Figure 7c that the increase in the sludge recycle ratio only gives a very little increment in VS removal efficiency. This is owing to the little amount of VS remaining in the digested sludge and thus recycling the sludge only increases the small amount of VS in the digester. Therefore, the final and initial VS present in the substrate are almost the same. According to Lee et al. [53], the volatile solid removal efficiency for a bench scale ACD of FW and SS ranges between 46.6 and 61.7%. From the three figures above, it can be noticed that the VS removal efficiency rangesfrom 55% to 72.5%, regardless of how the parameters vary within their given range.

3.4. Numerical Optimization Results

The numerical optimization function in the Design Expert v13 is used to select the most optimum value for the HRT, water to feed ratio, sludge recycle ratio and SS to FW ratio. The target of the study is set, which is to maximize the methane flow, COD and VS removal efficiencies in the ranges of 62.7 to 82.3% and 55.0 to 72.5%, respectively. Table 7 summarized the optimal value for the HRT, water to feed ratio, sludge recycle ratio and SS to FW ratio and the estimated value for the methane yield, COD and VS removal efficiencies' response.

Table 7. Summary of optimum value of independent variables and estimated response value.

HRT (Days)	Water to Feed Ratio	Sludge Recycle Ratio	SS to FW Ratio	Methane Flow (kg/h)	COD Removal Efficiency (%)	VS Removal Efficiency (%)
38.8	0.047	0.438	0.044	1495.25	81.8	69.2

3.5. Simulation Results

The process parameters value from Table 7 are entered into the SuperPro simulations with the water flowrate of 1186.2 kg/h, recycle ratio of 43.8% to the top stream for FSP-101 and residence time of 38.8 days in AD-101.

Table 8 shows the response parameters value obtained in the base case and optimized case and the percentage improvements is calculated. Based on Table 8, it can be concluded that the optimization results are successful since the improvement percentage is up to 52.6%. Methane yield generated from the AD of FW is normally ranging from 0.254 to 0.282 LCH4/g COD removed [54,55]. Besides, the methane yield for ACD of FW and sewage sludge is normally ranging from 0.18–0.38 L CH_4 g^{-1} VS_{added} [17,56,57]. Thus, both the methane yield generated from the base case and the optimized case are shown to be comparable with the literature findings. By comparing the optimized case with the estimated response value shown in Table 7, the methane flow obtained from the SuperPro simulations is 1494.23 kg/h, which is less than 0.07% difference with the estimated value using Design Expert. This shows that the results are reliable. Meanwhile, the COD removal efficiency achieved is 81.5%. Furthermore, the VS removal efficiency of 69.2% indicates that the simulation process outperforms the bench scale data of 46.6 to 61.7%.

Table 8. Base case and optimized case results.

Parameter	Base Case	Optimized Case	Percentage Improvements (%)
Methane flow	979.06 kg/h	1494.23 kg/h	52.6
COD removal efficiency	70.90%	81.50%	15.0
VS removal efficiency	59.40%	69.20%	16.5
Methane yield	0.25 L CH_4/g COD removed	0.29 L CH_4/g COD removed	16.0

The simulated biogas composition before and after upgrading is summarized in Table 9. A comparison of the biogas composition before upgrading with the literature data in terms of molar percentage is displayed in Appendix A Table A4. Based on Table A4, it can be noticed that all the components' compositions are in line with the literature values.

Table 9. Simulated biogas composition before and after upgrading.

Component	Before Upgrading		After Upgrading	
	Mass Flow (kg/h)	Composition (wt %)	Mass Flow (kg/h)	Composition (wt %)
Methane	1494.23	37.51	1494.230	38.86
Carbon dioxide	2349.77	58.98	2349.770	61.11
Hydrogen sulfide	39.47	0.99	0.001	0.00
Moisture	100.62	2.52	1.080	0.03
Total	3984.08	100.00	3845.08	100.00

Besides that, the treated effluent is required to meet the discharge effluent standards that complied with the Environmental Quality (Sewage) Regulations 2009 before discharging into the soil or water. Based on the simulated treated water characteristics shown in Table 10, it can be observed that the COD and BOD5 value of 14.04 mg/L and 8.78 mg/L meet the standard A discharge limit of 120 mg/L and 20 mg/L [42]. This concludes that the treated water is safe to discharge to the environment.

Table 10. Simulated treated water characteristics.

Parameter	Unit	Value
Ammonia	kg/h	39.47
Ash	kg/h	0.21
Biomass	kg/h	0.23
Carbohydrates	kg/h	0.00
Dead biomass	kg/h	0.33
Fats	kg/h	0.00
Proteins	kg/h	0.00
COD	mg/L	14.04
BOD5	mg/L	8.78

3.6. Economic Analysis

In this section, economic analysis for the anaerobic co-digestion of FW and SS is conducted. The economic calculations are completed using the economic evaluation functions in the SuperPro Designer. The purchase cost of the equipment is shown in Table A5.

The equipment data are based on January 2000 cost with a cost index of 435.8 and the cost is then adjusted to year 2021 in the SuperPro Designer. Generally, the lifetime for an AD plant is assumed to be 20 years [58]. Accordingly, the annual operating hours for modern chemical plants is 8000 h [59]. Thus, these two figures are used in the economic evaluations. Table 11 summarizes the unit cost for the products, raw materials and waste treatment used in the economic evaluations. The upgraded biogas, dried sludge and carbon credit are the revenue in the process plants. The BTF effluent, moisture from dehumidifier, aerobic emission, discharge solvent from belt filtration and GM filtration are categorized as aqueous waste which required further treatment before discharging into the environment. Food waste and sewage sludge are assumed to be zero cost as they are waste products that are required to be treated in order to reduce environmental issues.

Table 11. Unit cost for products, raw materials and waste treatment.

Item	Unit	Category	Values	Source
Upgraded biogas	$/kg	Revenue	0.360	[60]
Dried sludge	$/kg	Revenue	0.132	[61]
Carbon credit	$/kg	Revenue	0.007	[62]
Coagulant	$/kg	Operating Cost	0.450	[63]
Aqueous waste	$/kg	Operating Cost	0.002	[64]

3.6.1. Economic Analysis Results

Table 12 provides the summary of the economic evaluation for this project. With an annual total revenue of $13.4 million, the payback period achieved is 6.2 years with ROI of 16.0%. The net present value (NPV) is the sum of the present values of each individual cash flow over the 20 years of the project's life. NPV takes into account the time value of money by investigating the estimated future cash flows and discounting them to the present time [65]. NPV is the major factor to determine whether the investment is feasible. For NPV < 0, it shows that the investment is unacceptable as it might not make a return in the future. The NPV at 7.0% interest for this project is $5.28 million, which shows that the project is an acceptable investment. Meanwhile, the internal rate of return (IRR) is defined as the discount rate which makes the NPV of the cash flow to be zero [66]. According to Seadi et al. [67], a biogas plant project with less than 9% IRR is not worth the investment. An IRR of 10.23% obtained in this co-digestion process proves that this project is worth continuing.

Table 12. Summary of economics evaluation.

Item	Unit	Values
Total capital investment	$	19,694,000
Operating cost	$/yr	11,062,000
Total revenues	$/yr	13,445,000
Cost basis annual rate	kg MP/yr	30,760,628
Unit production cost	$/kg MP	0.36
Unit production revenue	$/kg MP	0.44
Gross margin	%	17.72
Return on investment (ROI)	%	16.02
Payback period	year	6.24
Internal rate of return (IRR)	%	10.23
Net present value (NPV)	$	5,283,000

3.6.2. Sensitivity Analysis

Sensitivity analysis is a method to determine the effects of uncertainties in the future on the viability of a project [64]. This analysis is performed by varying each of the parameters individually and the output is the parameter which has the most direct effect on the project viability, such as NPV. In this section, the unit price for the products (upgraded biogas, dried sludge and carbon credit) are varied with a range of ±20% of base cost while the capital cost is kept constant to determine the effect on NPV [64].

Figure 8 shows the sensitivity analysis of the ACD of FW and SS. The sales price of upgraded biogas, carbon credit and dried sludge is changed to determine the effect on NPV. From the diagram, it can be seen that the upgraded biogas is the most sensitive parameter. A slight alteration in the upgraded biogas sales price contributes significant changes to the NPV. Negative NPV is seen if the upgraded biogas unit price decreases by 10% or more. This is expected as the upgraded biogas selling price is the highest compared to the dried sludge and carbon credit, making it the major contribution to the total revenues as well as the NPV. Its selling price is 2.7 times and 51.4 times more than the dried sludge and carbon credit. It can be said that the project is no longer worth the investment if the selling price of biogas decrease is greater than 10% from its current price. Meanwhile, the changes in carbon credit unit prices have the least impact on the NPV. A horizontal line is discerned when the carbon credit prices vary by ±20%, indicating the effect is infinitesimal. This is due to a very low selling price of only $0.007/kg. The NPV is more sensitive to the dried sludge unit price than the carbon credit unit price, as the price is the second highest among all the three products.

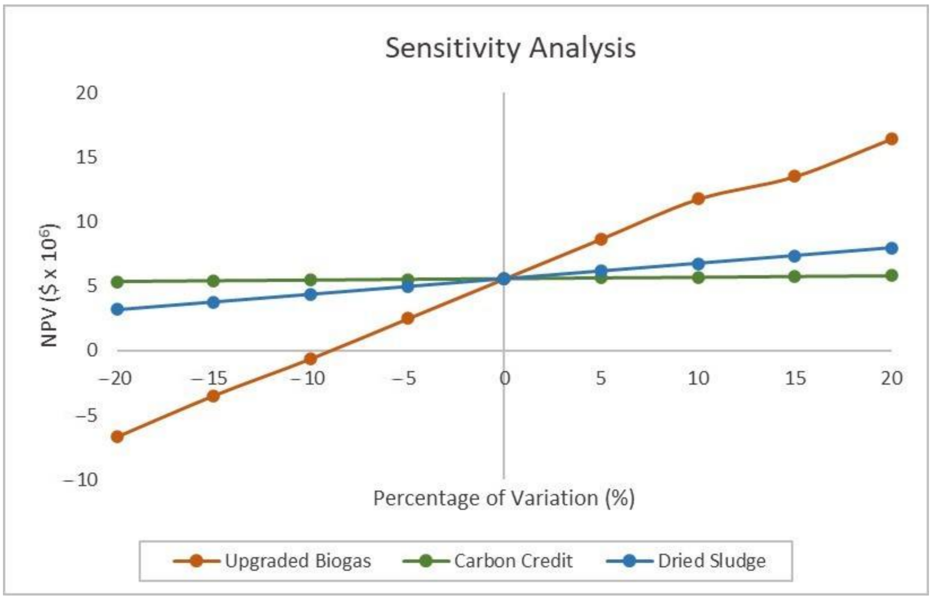


Figure 8. Sensitivity analysis.

4. Conclusions

The simulation model for biogas production from anaerobic co-digestion of food waste and sewage sludge is developed using SuperPro Designer v9.0. The base case using 10 days of HRT, zero ratio of water to feed, sludge recycle and SS to FW is first simulated and the methane yield of 0.25 L CH4/g COD removed and COD and VS removal efficiencies of 70.9% and 59.4% are obtained. Response surface methodology (RSM) in the Design Expert v13 software is utilized to study the effect of the hydraulic retention time (HRT), water to feedstock (kg/kg) ratio, sludge recycle ratio and the sewage sludge to food waste ratio (kg/kg) on the methane mass flow, COD and VS removal efficiencies while Box–Behnken Design (BBD) is used to perform the optimization. Based on the optimization results, by using HRT of 38.8 days, water to feed ratio of 0.047, sludge recycle ratio of 0.438 and SS to FW ratio of 0.044 and a methane yield of 0.29 L CH_4/g COD removed, COD and VS removal efficiencies of 81.5% and 69.2%, respectively, are achieved. The methane yield is 16% higher in the optimized case. Economic analysis is conducted and the results show that the project required a payback period of 6.24 years with ROI of 16.23%. The positive NPV of $5.28 million indicates that this project is feasible for investment. Lastly, sensitivity analysis is performed and the upgraded biogas selling price proves to be the most sensitive parameter affecting the NPV value. A comparable result of methane yield is achieved in this project with the literature value of 0.28 L CH_4/g COD removed, concluding that this project is feasible for large scale biogas production.

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Appendix A

Table A1. FW and SS feed mass flow and composition in simulations.

Component	Food Waste		Sewage Sludge	
	Mass Flow (kg/h)	Composition (wt %)	Mass Flow (kg/h)	Composition (wt %)
Moisture	19,221.92	80.3	890.30	83.80
Ash	454.82	1.90	40.37	3.80
Carbohydrates	2576.36	10.76	10.04	0.95
Proteins	939.22	3.92	101.62	9.56
Lipids	676.41	2.83	20.08	1.89
Biomass	68.94	0.29	0.00	0.00
Total	23,937.64	100.00	1062.41	100.00

Table A2. Equipment specifications.

Equipment	Parameter	Unit	Value	Source
Sterilizer	Sterilization temperature	°C	121	[29]
Anaerobic digester	Operating temperature	°C	35	[31]
	Retention time	h	931.2	Optimisation
Dehumidifier	Operating temperature	°C	5	[68]
Aerobic pond	Retention time	h	48	[39]
Secondary clarifier	Coagulant flowrate	kg/h	40.4	[69]

Table A3. Box–Behnken design matrix.

Run	A: HRT (Days)	B: Water to Feed Ratio	C: Sludge Recycle Ratio	D: Sewage Sludge to Food Waste Ratio
1	25	0	1	0.5
2	25	0.5	1	0
3	40	0.5	0	0.5
4	25	0	0.5	1
5	40	0.5	0.5	1
6	40	1	0.5	0.5
7	25	0.5	0.5	0.5
8	25	0.5	0.5	0.5
9	10	0.5	1	0.5
10	40	0.5	1	0.5
11	40	0	0.5	0.5
12	25	1	0.5	1
13	25	0.5	1	1
14	25	0.5	0.5	0.5
15	10	0.5	0.5	1
16	25	1	0.5	0
17	10	0.5	0.5	0
18	25	1	0	0.5
19	25	0.5	0.5	0.5
20	25	0.5	0	1
21	25	0	0	0.5
22	25	0.5	0	0
23	25	1	1	0.5
24	40	0.5	0.5	0
25	10	0	0.5	0.5
26	10	1	0.5	0.5
27	25	0.5	0.5	0.5
28	25	0	0.5	0
29	10	0.5	0	0.5

Table A4. Simulated biogas composition versus literature biogas composition.

Component	Composition (vol %)	
	Literature	Simulations
Methane	55–65	59.16
Carbon dioxide	35–45	35.02
Hydrogen sulfide	0–1	0.74
Moisture	1–5	3.59

Table A5. Equipment purchase cost.

Equipment	Capacity Measure	Unit Capacity	Unit Cost ($)	Source
Anaerobic digester	Vessel volume (L)	14,162,231.27	1,696,000	[70]
Bio-trickling filter	Surface area (m^2)	0.219	113,000	[32]
Dehumidifier	Condensation area (m^2)	7.96	45,000	Simulations
Primary clarifier	Surface area (m^2)	61.45	73,000	[32]
Secondary clarifier	Surface area (m^2)	57.41	73,000	[32]
Aerobic pond	Vessel volume (L)	1,132,596.36	272,000	[70]
Granular media filter	Volume (L)	0.42	13,000	[32]
Belt press filter	Belt width (m)	2.37	75,000	[32]
Sludge dryer	Evaporative capacity (kg/h)	1980.33	42,000	Simulations
Unlisted equipment		-	374,000	Simulations

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