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Simulation and Optimization of Anaerobic Co-Digestion of Food Waste with Palm Oil Mill Effluent for Biogas Production

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Abstract: Food waste (FW) utilized as substrate for anaerobic digestion (AD) to produce biogas is promising. Simultaneously, waste is handled and value-added products such as biogas and fertilizer are produced. Palm oil mill effluent (POME) is used as the co-substrate. This study aims to simulate the complete process flow of anaerobic co-digestion (AcoD), consisting of pre-treatment of feedstock, biogas upgrading, wastewater treatment and sludge dying using SuperPro Designer. Parameters, namely hydraulic retention time (HRT), recycle ratio of sludge, water to FW ratio (kg/kg) and co-substrate to FW ratio (kg/kg), would affect the performance of digester. The optimization of these parameters is performed using Design-Expert software, involving response surface methodology (RSM). The effects on responses such as methane flow, chemical oxygen demand (COD) and volatile solid (VS) removal efficiencies are analyzed. In treating 25,000 kg/h of feed, the optimized values for HRT, recycle ratio, water to feedstock ratio, POME to FW ratio are 37.2 days, 0.381, 0.027 and 0.004, respectively. The methane yield is 0.30 L CH_4/g of COD removed, with COD and VS removal efficiencies of 81.5% and 68.9%, respectively. The project is profitable, with a payback period of 6.14 years and net present value (NPV) of $5,680,000. A comprehensive understanding of AD matures it for commercialization purposes.

Keywords: anaerobic digestion; food waste; palm oil mill effluent; gas production; optimization

1. Introduction

Food waste (FW) is inevitably generated throughout the whole food supply chain (FSC), from production to packaging, processing to distribution, and finally through consumption [1]. FW is defined as consumable food for humans that is thrown, decayed, deteriorated or infested by pests that originate at any stage of the FSC [2]. The alarming statistics result in negative impact towards the environmental, social and economic aspect. According to Chamhuri et al. [3], each Malaysian generates approximately 1 kg of FW daily. FW generated per week at municipal areas in Selangor such as Petaling Jaya, Kajang and

Subang Jaya are amounted to 3959.17, 1800.82 and 2057.06 tons, respectively [4]. It can be observed that FW is generated at an alarming rate.

Currently, the methods employed to handle FW in Malaysia are landfilling and incineration. Disposal of FW to landfill poses several issues. Improper disposal leads to foul odors during decomposition and thus attracts pests. Furthermore, as FW decays, greenhouse gases are emitted into the atmosphere. The availability of landfill is also limited [5]. For incineration, it is costly and energy intensive. Combustion of FW is also an obstacle, as it has a high moisture content, roughly 80% [6]. Moreover, the energy generated is low due to its low calorific value. Another undesirable effect is the release of dioxins to the environment which is detrimental to human health.

A more sustainable method involving conversion of waste to energy (WTE) technology, anaerobic digestion (AD) of FW is being explored. AD of FW has several benefits. Organic matter such as carbohydrate, protein and lipid can be degraded into intermediates and finally biogas. The typical biogas volume composition is 50–75% methane, 25–45% carbon dioxide (CO_2), 2–7% water vapor, less than 2% ammonia and less than 1% hydrogen sulfide (H_2S) [7]. The ideal pH range is between 6.5 and 7.5 [8]. Thus, ensuring optimum bacterial activity enhances the production of biogas. Value-added product such as biogas and digestate can be produced. It is a source of renewable energy. Biogas generated can be used as fuel, combusted to generate heat and electricity. With AD of FW, captured biogas can be utilized. This eliminates direct emission of methane gas which lead to global warming, thus benefiting the environment.

The disposal of FW poses an environmental issue due to the emission of methane gas and hence must be handled properly. As it is a suitable feedstock for AD, waste can be transformed into energy via a sustainable method. While biogas production via AD of FW is a mature technology, there is still problems of system stability and optimisation, low production rate, and commercialization. It is of utmost importance that the operating parameter should be kept at optimum condition for maximized digester performance. In this work, several parameters are investigated such as hydraulic retention time (HRT), recycle ratio of anaerobic sludge, water to feedstock ratio (kg/kg) and substrate to FW ratio (kg/kg). HRT ensures the complete degradation of organic matter within the digester. The longer the HRT, the higher the methane flow and chemical oxygen demand (COD) removal efficiency. Recycling part of the anaerobic sludge back to the digester is beneficial as it helps to produce more methane. This aids in degrading complex organic matter. Moreover, sludge that is rich with microbe can be recycled back into the digester. The addition of water also helps in enhancing the volatile solids (VS) reduction. Anaerobic co-digestion (AcoD) is beneficial in producing more biogas. Co-substrate helps in enhancing digester performance and stability as a balance of nutrients and dilution of toxic occurs.

During the production of crude palm oil, wastewater known as Palm Oil Mill Effluent (POME) is generated in large volume. Malaysia is one of the largest producers of palm oil globally. Somewhere between 2.50 and 3.75 tons of POME are produced per ton of crude palm oil produced. This indicates that over half of the water used in manufacturing process ends up as wastewater. Hence, it is widely available. POME is rich in soluble organic matter and has COD content ranging from 44 to 103 g/L [9] and, thus, it cannot be directly discharged into the environment. Therefore, it is excellent as a co-substrate in this simulation. AcoD is advantageous as the nutrients are balanced and toxicity is reduced, boosting stability and efficiency of AD [10].

All in all, AcoD of FW is a promising technology that offers substantial benefits in aspects such as social, economy and environmental. This method helps in moving up the waste hierarchy and reduce methane emission. It is also in line with the Malaysia Government Policy in Green Technology Master Plan 2017–2030 on FW management where FW discarded into landfill is reduced and processed to form valuable products and proper treatment of FW [11]. Globally, there is a shift in energy source from fossil fuels to bioenergy [12]. Therefore, research on improving, enhancing, and maturing of AcoD of FW is crucial as waste can be efficiently handled and simultaneously generate energy.

Thus, the aim of this study includes the simulation of the AcoD using SuperPro Designer which has not been conducted thus far. This software was founded by a company called "INTELLIGEN" in 1991 to commercialize computer-aided process design technology. It is a useful tool as it provides environmental properties of the streams such as COD value as well as the reactions kinetic models required in this study such as Monod kinetic model. Simulation enables modelling of AD process to be carried out in a shorter duration. A better understanding can be obtained before performing experimental works. Simulation is also more time and cost efficient. Hence, the flowsheet will include the pre-treatment of feedstock, AD, biogas upgrading, wastewater stabilization and sludge drying. Furthermore, the parameters affecting the methane produced, COD and VS removal efficiencies will be analyzed using Design-Expert software. This provides a comprehensive understanding on how to optimize and maximize the biogas production. Response surface methodology (RSM) will be employed to analyze the parameters involved on the responses by integrating mathematical and statistical techniques [13]. Box-Behnken Design (BBD) will be used. The combined effect of parameters on the AD process can be indicated using mathematical expression and graphical 3D images. After optimization, economic analysis is conducted. This determines the viability and profitability of the project. Improvements were also listed to increase the reliability of the simulation.

2. Materials and Methods

2.1. Characteristic of Feedstock

The composition of FW and POME used in the simulation in SuperPro Designer is displayed in Table 1. The optimum flowrate of FW and POME required will be obtained after optimization. Considering the statistics mentioned in the introduction section, the total feedstock (FW and POME) will be 25,000 kg/h.

Table 1. Composition of FW and POME.

Component	Mass Composition (%)	
	FW	POME
Carbohydrate	10.76	2.53
Protein	3.92	0.56
Fat	2.83	0.60
Biomass	0.29	0.85
Ash	1.90	0.45
Water	80.30	95.02
References	[6]	[14]

2.2. SuperPro Designer Simulation

The flowsheet is divided into 4 sections, namely: pre-treatment of feedstock (red), AD (orange), biogas upgrading (purple) and wastewater stabilization plus sludge drying (blue), as indicated with the different colors in Figure 1. The total feed flowrate to be treated will be 25,000 kg/h. The optimization of parameters affecting AD will be carried out Design-Expert Software.

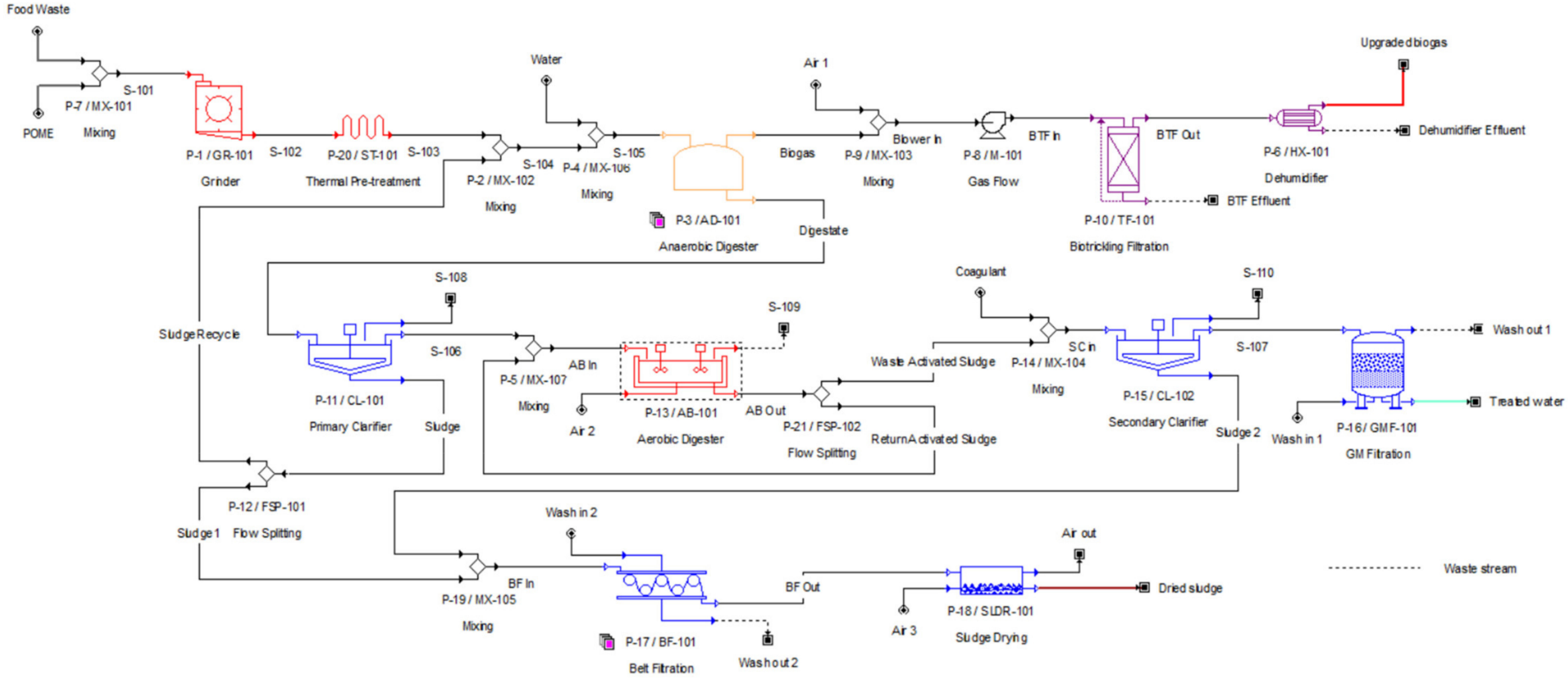


Figure 1. Flowsheet for biogas production simulated using SuperPro Designer.

2.2.1. Pre-Treatment of Feedstock

Before AD, pre-treatments are required. This includes mechanical and thermal pre-treatment. The mechanical treatment involves reduction in size. By passing through a grinder, particles can have a similar size distribution. Reduction in particle size increases solubilization of organic material [15]. The surface area exposed to contact with microorganisms also increases. Thus, the degradability of organic material increases, enhancing methane generation. Thermal pre-treatment such as sterilization must be conducted on FW prior to or after AD [16]. Besides, thermal pre-treatment before AD causes the breakdown of complex molecules such as polysaccharides and protein into smaller molecules and releasing the organic content into the liquid phase. Sterilization is carried out at 121 °C [17].

2.2.2. AD Process

AD is a complex process where parameters involved should be maintained at optimal value for high quality and quantity biogas production. Mesophilic digestion is carried out with an operating temperature of 35 °C [8]. This provides benefits such as higher stability for optimum biogas production. Furthermore, energy requirement is drastically lowered, reducing operational costs. Monod kinetics will be used in the simulation as it is considered a standard model for AD and it is well developed in microbial kinetics [18]. The kinetic parameters used in simulations are tabulated in Table 2. Methane flow obtained will be used for methane yield calculation as illustrated in Equation (1). Parameters that affect the amount of methane produced and the removal efficiencies of COD and VS will be analyzed. COD removal efficiency is calculated using Equation (2) [19]. Equation (3) shows the formula for VS removal efficiency [20].

$$\text{Methane yield} = \frac{Q_{CH_4}}{Q_{in} \times COD_i \times \text{COD removal efficiency}} \tag{1}$$

where,

Q_{CH4} = Volumetic flowrate of methane produced $\left(\frac{m^3}{h}\right)$

Q_{in} = Volumetic flowrate of feed $\left(\frac{m^3}{h}\right)$

COD_i = Influent COD before AD $\left(\frac{mg}{L}\right)$

$$\text{COD removal efficiency, \%} = \left(1 - \frac{COD_i}{COD_f}\right) \times 100 \tag{2}$$

where,

$$COD_f = \text{Effluent COD at digestate after AD} \left(\frac{mg}{L}\right)$$

$$\text{VS removal efficiency, \%} = \left(1 - \frac{VS_i}{VS_f}\right) \times 1 \tag{3}$$

where,

VS_i = Influent VS before AD $\left(\frac{mg}{L}\right)$

VS_f = Effluent VS at digestate after AD $\left(\frac{mg}{L}\right)$

Table 2. Kinetic parameter for AD simulation in SuperPro Designer.

Kinetic Parameter	Component	Value	Reference
Degradation constant (1/h)	Carbohydrate	0.0521	[21]
	Protein	0.0333	
	Fat	0.0292	
Monod constant (mg/L)	–	465.00	[22]

2.2.3. Biogas Upgrading

Biogas has to be pre-cleaned and upgraded to biomethane to remove H_2S and water vapor [23]. The presence of H_2S leads to the corrosion of equipment and is hazardous to human health. Furthermore, combustion of H_2S produces sulfur dioxide. This contributes to acid rain. H_2S must be reduced to 200–500 ppmbefore utilization. Therefore, the biotrickling filter is employed, a biologically based removal method. Bio-desulfurization is performed through the microbial activity of microorganisms from the families of Thiobacillus, Thiomonas and Paracoccus. Compared to the physical-chemical method, the superiorities of this method include: being carried out under mild operating conditions, less energy intensive, more cost efficient and reduced secondary pollutant emissions. H_2S is converted into elemental sulfur and sulphate as shown in Appendix A [24].

When temperature drops, water vapor condenses causing residual H_2S and CO_2 dissolves. This leads to corrosion of pipes and equipment. Hence, it is crucial to remove water from the biogas mixture. Moisture removal also increases the methane content in biogas. Biogas will be cooled to its dew point of 5 °C [24]. A heat exchanger system–dehumidifier is used to remove the water content. Freon is used as the coolant as it is a cheaper option as indicated in SuperPro Designer. Upgraded biogas can be used as fuel to generate electricity or heat through combustion [24].

2.2.4. Wastewater Stabilization and Sludge Drying

Digestate from AD will enter the primary clarifier. Some of the settled solid contents will be recycled back into the digester and the remaining will be sent to belt filtration. The top part will undergo aerobic oxidation. A combination of AD and aerobic oxidation is advantageous in treating high organic pollutant in wastewater. Firstly, organic load for aerobic digestion can be reduced as organic matters in AD degrade. Moreover, efficiency of aerobic process is enhanced as anaerobic treatment alters the biochemical property of the wastewater [25]. Aerobic oxidation is the breakdown of organic material in the presence of oxygen to produce CO_2. Table 3 shows the kinetic parameter used in the simulation. This process can be represented by Equations (4) and (5) [26].

$$\text{Organic material} + O_2 \rightarrow \text{cellular matter} + CO_2 + H_2O \tag{4}$$

$$\text{Cellular matter} + O_2 \rightarrow \text{digested sludge} + CO_2 + H_2O \tag{5}$$

Table 3. Kinetic parameter of aerobic oxidation simulation in SuperPro Designer.

Kinetic Parameter	Value	Reference
Degradation constant (1/h)	0.1260	[27]
Monod constant (mg/L)	21.23	[28]

Waste stabilization is natural, involving bacteria and algae. Algae should be retained at the top of the pond for exposure to sunlight and prevent its removal from the bottom together with the sludge. During photosynthesis, algae use CO_2 produced during aerobic degradation and produce oxygen required for aerobic degradation. This is beneficial in economical, operation and energy requirement aspect. Typically, a detention time between 2 and 6 days are required [29]. In this simulation, a detention time of 2 days is used. As bacteria are influential in the degradation of organic matter, 5% of the outlet of aerobic pond (returned activated sludge) is recirculated back into the aerobic pond. Next, the effluent will be introduced into the secondary clarifier. This enables the sedimentation of the biological solids formed from the previous aerobic treatment process.

In accordance with the Environmental Quality Act 1974, effluent discharge must meet the Malaysia Environmental Quality (Sewage and Industrial Effluents) Regulations. Parameter and its limit of effluent are as shown in Table 4.

Table 4. Parameters and limit of effluent discharge [30].

Parameters	Unit	Standard A	Standard B
BOD_5	mg/L	20	50
COD		50	100
Suspended solids		50	100

In the secondary clarifier, alum, a coagulant is added. Coagulant is added to help fine solid particles to clump and coalesce together reducing the settling time. This helps in increasing the removal of COD, biochemical oxygen demand (BOD_5) and total solids (TS) from wastewater before entering the granular media (GM) filtration unit. The solids settle at the bottom of the tank will be removed and dried to produce fertilizer. The amount of coagulant required is obtained using Equation (6) [31,32]. The flowrate treated is in millions of gallons per day (MGD). The dosage of coagulant used is 635 mg/L [32]. The amount of coagulant required in the secondary clarifier is 40.00 kg/h.

$$\text{Coagulant required}, \frac{\text{lbs}}{\text{day}} = \text{Flowrate, MGD} \times \text{chemical dosage}, \frac{\text{mg}}{\text{L}} \times 8.34\frac{\text{lbs}}{\text{gallon}} \tag{6}$$

Belt filtration helps in removing moisture content before drying. Solid content after belt filtration is 30%. The solid content after sludge dryer is 75%. The final product is dried sludge which can be sold as fertilizer.

2.3. Statistical Analysis Using Design-Expert Software

RSM was used to investigate the effects of independent variables such as HRT (A), recycle ratio of anaerobic sludge (B), water:feedstock ratio (kg/kg) (C) and POME:FW ratio (kg/kg) (D) on response variable such as methane flow (kg/h), COD removal efficiency (%) and VS removal efficiency (%) of the digestion process. These parameters can be investigated and optimized for maximum biogas production. RSM is separated into two multi-level designs, namely central composite design (CCD) and BBD. Here, BBD was employed. It is a spherical, rotatable or nearly rotatable second-order design. The benefits of this compared to CCD is the design matrix is less complex, with lesser experimental runs. Hence, it is more cost efficient and a viable tool [33]. For HRT, the lower bound is 10 while the upper bound is 40 days, as typical HRT between 10 and 40 days [8]. The remaining 3 independent variables have a lower bound of 0 and upper bound of 1. Table A1 (Appendix A) shows the experimental design and raw data for analysis in Design-Expert.

Analysis of variance (ANOVA) was used for the graphical study and evaluation of the data. The adequacy of the fitted polynomial model was also verified using the coefficient, R^2. Regression analysis of simulation data was conducted to plot the 3D response surface plot. The significance of model terms was also evaluated using the probability value (p-value) at 95% confidence interval [34].

The development of model will be carried out using a second order polynomial equation. In this model, three responses as a function of the independent variable were illustrated in Equation (7). Positive coefficient infers synergistic effects while negative coefficient shows antagonistic effect.

$$\begin{aligned} Z = {} & \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D + \beta_{12} AB + \beta_{13} AC + \beta_{14} AD + \beta_{23} BC \\ & + \beta_{24} BD + \beta_{34} CD + \beta_{11} A^2 + \beta_{22} B^2 + \beta_{33} C^2 + \beta_{44} D^2 \end{aligned} \tag{7}$$

where,

β_o = Constant
β_j = Linear coefficient
β_{jj} = Quadratic coefficient
β_{jk} = Interactive coefficient

3. Results and Discussion

3.1. Methane Flow

Table A2 (Appendix A) summarizes the ANOVA for the response surface quadratic model for methane flow. The probability value, $p < 0.05$ is assumed to be significant whereas $p > 0.10$ is insignificant [35]. The response model is highly statistically significant with a 95% confidence level. The F- and p-value are 1124.95 and lesser than 0.0001 as seen in Table A2. Hence, there is only a 0.01% chance that F-value this large could occur due to noise. Moreover, it is observed that all the 4 parameters are significant model terms with $p < 0.0001$. Most of the interactive parameters are significant. Models with $p > 0.10$ are not significant such as C^2.

A standard deviation (SD) of 5.44 is obtained. The model's fit and accuracy is evaluated using the coefficient of variation (CV) and coefficient of determination, R^2. The lower the CV value obtained, the higher the reliability [36]. For the methane flow model, the CV obtained is 0.47%, which is sufficiently low. Furthermore, the R^2 obtained is 0.9992. As stated by Ghaleb et al. [37], for a good statistical model of the best fit, R^2 should be between 0.75 and 1. This shows that the results obtained from the simulation are close to the predicted response. The adjusted R^2 measures the amount of variation from the mean in the model [34]. Closeness of R^2 and adjusted R^2 indicates the adequacy of the model. The predicted R^2 indicated how well the regression model predict the response for new observation [38]. The adjusted and predicted R^2 are also align with each other as their difference is less than 0.2 [35]. Furthermore, adequate precision measures the signal to noise ratio. A ratio greater than 4 is desired and this provides indication that the model can be used to navigate the design space [35]. From Table A2, the value obtained is 123.34.

The regression equation in terms of coded factor for methane flow is as shown in Equation (8).

$$\begin{aligned}\text{Methane flow} = \; & 1175.78 + 70.30A + 31.90B - 56.29C - 170.27D - 13.42AB \\ & +4.96AC - 27.87AD^{*} + 14.98BC - 17.67BD + 27.02CD \\ & -37.21A^2 - 7.00B^2 - 3.52C^2 + 21.19D^2\end{aligned} \tag{8}$$

As seen in Figure 2, POME:FW ratio (D) has the steepest slope, indicating the greatest impact on methane flowrate. The TS in POME is only 4.98% whereas in FW is 19.70%. This indicates that the amount of organic matter available for degradation in POME is lower. Recycle ratio (B) has the least impact on methane production. Effect of HRT (A) and water:feedstock ratio (C) is similar. However, increasing A, increases methane generated, while the vice versa occurs for C.

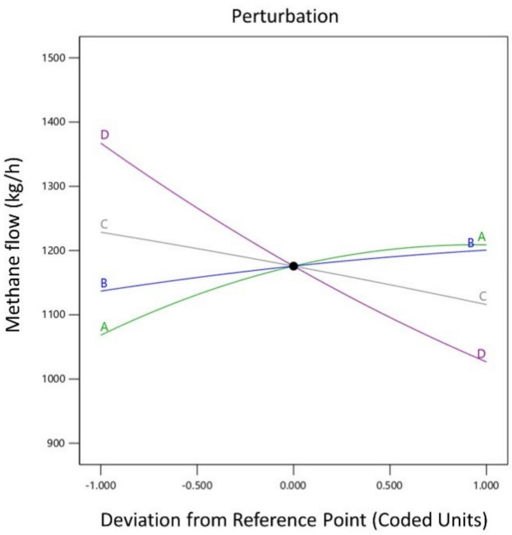


Figure 2. Sensitivity analysis of parameters on methane flow.

As observed in Figure 3a,b, HRT exerts a quadratic effect on the methane flow from the digester. When the HRT increases, the methane production is enhanced. With mesophilic digestion, a longer HRT is required. HRT is the average time the liquid digestate remains in the digester. At a lower temperature, substrate utilization and microbes develop at a slower pace. Typically, an HRT between 10 and 40 days is required [8]. Organic matter with sufficient time in the digester can completely degrade. Methanogens, crucial in producing methane, have a longer regeneration period compared to acidogenic bacteria. Consequently, a higher HRT is preferred to retain the methanogens [39]. Additionally, if a substrate has high cellulose and fiber content, a longer retention time is preferred. These components are harder to hydrolyze and is the rate limiting step [40]. However, a longer HRT increases the volume of reactor, incurring a higher cost. Thus, HRT optimization must be conducted. Figure 3a indicates that the highest methane production is obtained with HRT of 40 days and recycle ratio of 100%.

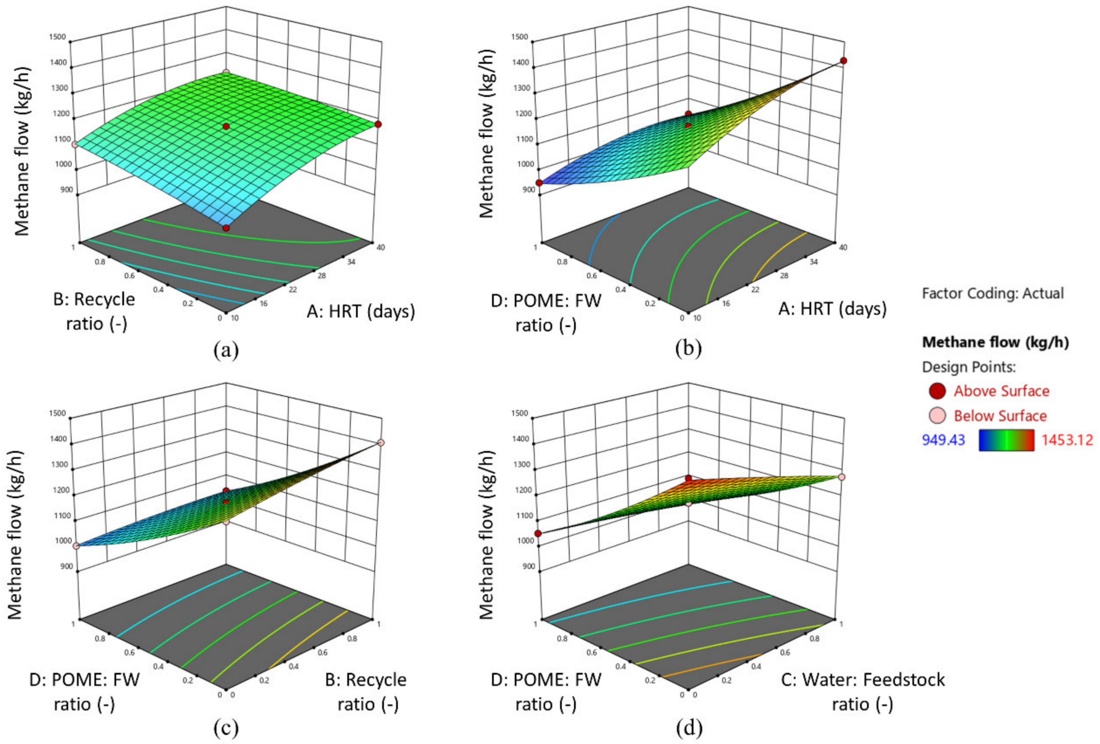


Figure 3. 3D response surface plot for methane flow: (**a**) Combined effect of HRT and recycle ratio; (**b**) Combined effect of HRT and POME: FW ratio; (**c**) Combined effect of recycle ratio and POME:FW ratio; (**d**) Combined effect of water: feedstock ratio and POME: FW ratio.

From Figure 3c, the recycle ratio has a positive linear effect on the methane mass flowrate. Digestate leaving the digester is still actively producing methane [41]. Furthermore, bacteria are simultaneously removed. Thus, a water-solids mixture which is rich with microbes from the bottom of the primary clarifier will be reintroduced. Recycling sludge also helps to provide some alkalinity into the digester for optimum bacterial activity [42]. Biomethane potential can be greatly enhanced when organic matter spends longer time in the digestate. This enhances the degradability of components that are harder to digest [43].

The recycle ratio of digestate from primary clarifier is analogous to organic loading rate (OLR) of the digester. OLR is the amount of dry organic matter that can be introduced into the digester per day per unit volume of anaerobic digester. A high OLR has an inhibitory effect on methanogens which reduces the methane production. Beyond the suitable OLR, fatty acids start to accumulate which reduces the pH of the digester [8]. The effect of high recycle ratio is not evident in this simulation as the production of fatty acid is not accounted for.

AcoD involves the digestion of two or more different feedstocks. The benefits of AcoD involves better biogas yield, increasing the economic viability of the plant [44]. With the mixing of feedstocks, a macro- and micro-nutrient equilibrium and moisture balance can be achieved. Inhibitory or toxic compound can be diluted [10]. All of this aids in increasing the digestion performance. Nevertheless, at a high concentration, inhibition occurs [45].

As POME:FW ratio increases, the methane flow from digester decreases as seen in Figure 3c. The biogas produced depends on the amount of carbohydrate, protein and fats present in the feedstock. For POME, the water content is 95.02%. Consequently, organic matter content available for degradation is lower. As fewer organic matters are present, less methane is produced. Besides, the synergic effect of microorganism, nutrient balance between the two substrate and process stabilization cannot be reflected through the simulation. Another limitation is that the nutrients are not considered in the digestion performance.

From Figure 3d, water addition has a linear effect on methane mass flow. As moisture content increases, the methane flow decreases [46,47]. With reduced moisture content, the total solids present are higher. This indicates that more organic matters are present for degradation to produce methane. Moreover, microbial flora is also present to a greater extent. This consortium of bacteria is crucial in the digestion of different stages in AD [48]. Another possible explanation is that the addition of water causes organic matter, nutrient and microorganisms to be washed out at a greater pace. Thus, incomplete degradation of organic matter occurs. Methane flow is the highest without water addition as observed in Figure 3d.

From Figure 3, the highest methane generation can be obtained when the HRT is high, the recycle ratio is high, low water:feedstock ratio and low POME: FW ratio. However, these parameters also affect COD and VS removal efficiencies which will be explored next.

3.2. COD Removal Efficiency

Table A3 shows the results of ANOVA for response surface quadratic model for COD removal efficiency. The response model is statistically significant with an F- and *p*-value of 498.66 and lesser than 0.0001. The likelihood of an F-value this large occurring due to noise is only 0.01%. Likewise, it is observed that the 4 parameters involved are significant model terms with *p*-value lesser than 0.05. AC is the only insignificant model with *p*-value of 0.1124. A low standard deviation, 0.13 means that the dispersion of dataset with respect to mean is low, a reliable result. The model is accurate with suitable CV, R^2 and adequate precision value.

Equation (9) is the regression equation in terms of coded factor for COD removal efficiency.

$$\begin{aligned}\text{COD removal}\quad & \text{efficiency}\\ & = 80.9700 + 1.4200\text{A} - 2.3900\text{B} + 1.6100\text{C} - 0.5687\text{D}\\ & -0.3332\text{AB} - 0.1122\text{AC} - 0.3892\text{AD}^{*} + 0.1982\text{BC} - 0.5300\text{BD}\\ & +0.6789\text{CD} - 0.8269\text{A}^2 - 0.5542\text{B}^2 - 0.2995\text{C}^2 - 0.4929\text{D}^2\end{aligned} \tag{9}$$

From Figure 4, recycle ratio has the greatest impact on COD removal efficiency. Due to the introduction of more organic matter into the digester and not all can be degraded. The least impact is the change in POME: FW ratio, attributed to the lower organic content in POME.

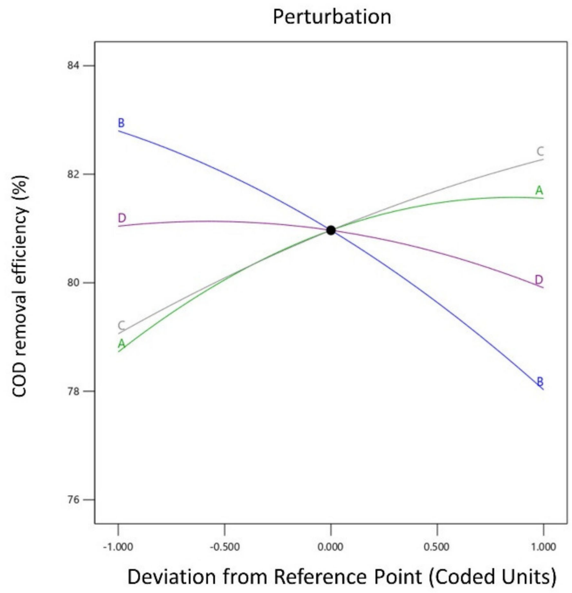
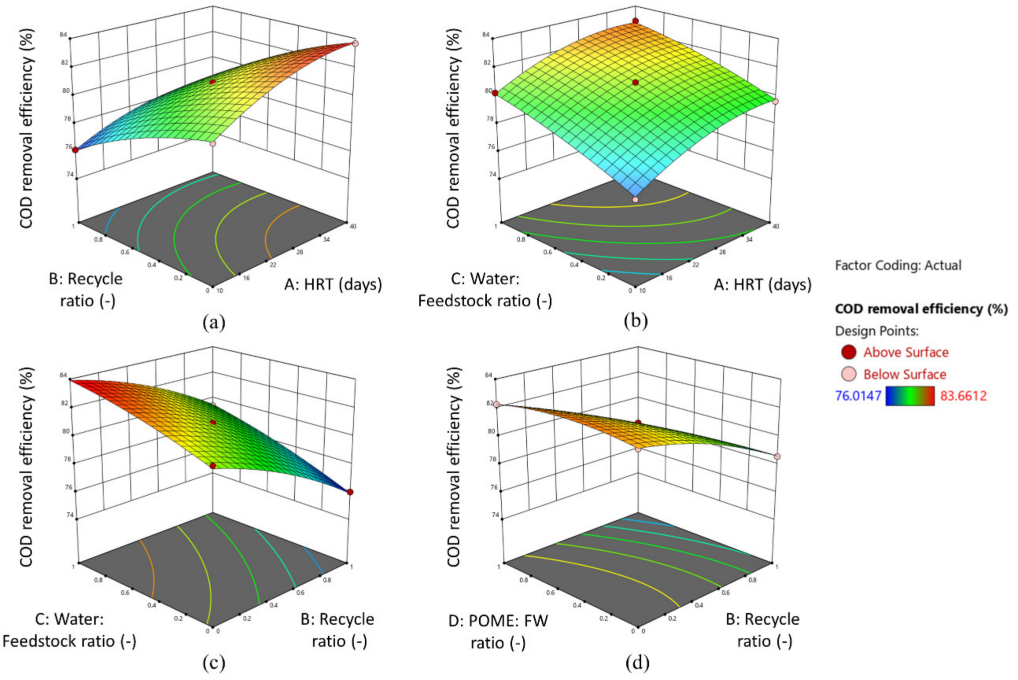


Figure 4. Sensitivity analysis of parameters on COD removal efficiency.

Figure 5a shows that both HRT and recycle ratio exerts a quadratic effect on the COD removal efficiency. A longer HRT enhances the COD removal efficiency as more methane is generated. Methane production can be estimated from COD reduction during AD as 0.35 m^3 of methane is produced from 1 kg of COD destruction, theoretical maximum amount [49]. However, with an increasing recycle ratio (OLR), the COD removal efficiency will decrease [50]. Nevertheless, the methane flow increases. COD removal efficiency reduces as more organic matter are introduced into the digester and not all the organic matter will be digested, thereby reducing the rate of COD destruction. For high COD removal efficiency, a long HRT and zero recycle of sludge is preferred.



(a) (b) (c) (d)

Figure 5. 3D response surface plot for COD removal efficiency: (**a**) Combined effect of HRT and recycle ratio; (**b**) Combined effect of HRT and water: feedstock ratio; (**c**) Combined effect of recycle ratio and water:feedstock; (**d**) Combined effect of recycle ratio and POME:FW ratio.

As shown in Figure 5b, as water content increases, the COD removal efficiency increases. With the addition of water, the COD content in the feedstock can be diluted. The highest COD destruction is observed with HRT of 40 days and water: feedstock ratio of 1. A long HRT ensures organic materials are digested and converted into methane.

As illustrated in Figure 5c, COD removal efficiency is the lowest with a complete recycle of sludge and water to feedstock ratio of 0. Water is a reactant in the hydrolysis reaction and helps to solubilizes organic matter. As water is not added, the rate of digestion decreases, reducing COD destruction rate.

The effect of POME:FW ratio has a quadratic effect on COD removal efficiency as observed in Figure 5d. However, the effect of POME:FW ratio does not have a significant impact on COD removal efficiency. Despite that, a high COD removal efficiency is achieved when POME to FW ratio is 1 with 0 recycle ratio due to the high-water content in POME.

To summarize, for a high COD removal efficiency, the HRT and water:feedstock ratio should be maximized whereas the recycle ratio should be minimized.

3.3. VS Removal Efficiency

Table A4 presents the ANOVA for response surface quadratic model for VS removal efficiency. F- and *p*-value are 488.93 and <0.0001, respectively. This shows that the model has a significant contribution against the output at a 95% confidence interval. Moreover, the chance of F-value this large occurring due to noise is just 0.01%. The four independent variables are significant model terms. AC is an insignificant model term. The model is accurate with suitable CV, R^2 and adequate precision value.

The regression equation in terms of coded factor for VS removal efficiency is shown in Equation (10).

$$\begin{aligned}\text{VS removal}\quad & \text{efficiency}\\ & = 67.2400 + 0.8408A - 1.6300B + 3.7700C - 3.3900D\\ & -0.2109AB - 0.1278AC - 0.5083AD^{*} - 0.2578BC - 0.2088BD\\ & +1.3000CD - 0.5061A^2 - 0.2295B^2 - 0.5673C^2 - 0.2290D^2\end{aligned} \tag{10}$$

VS removal efficiency is least affected by changes in HRT as observed in Figure 6. Both C and D affects the VS reduction in digester to a greater extent. As C increases, the VS removal efficiency enhances. However, increase in D has a reverse effect where VS removal rate reduces.

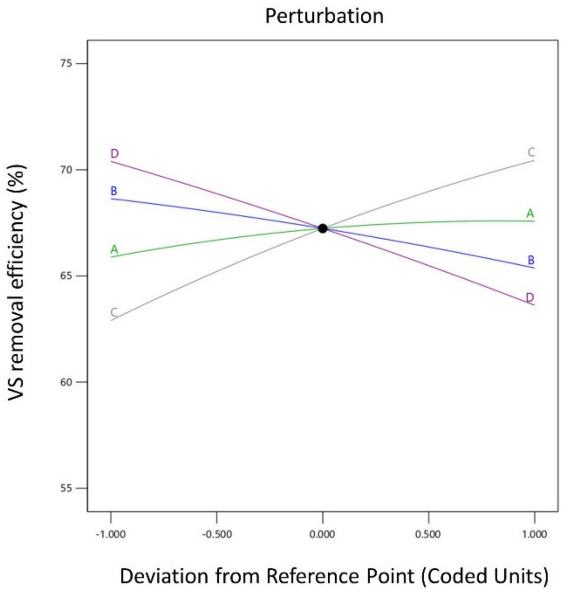
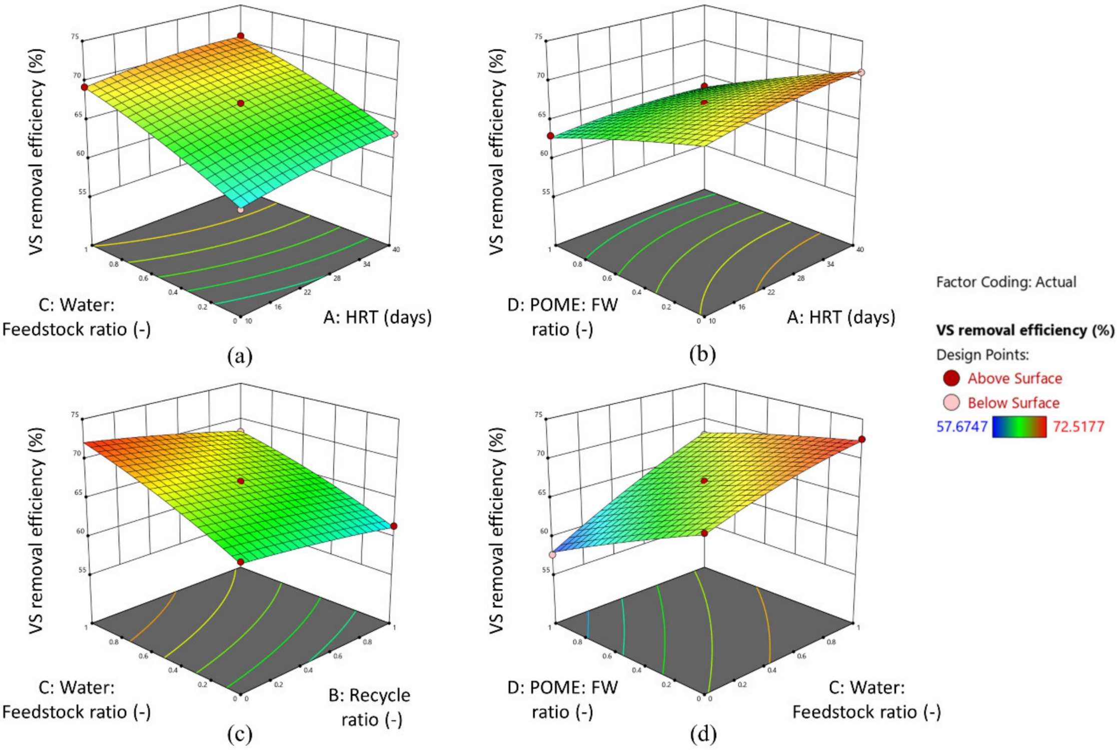


Figure 6. Sensitivity analysis of parameters on VS removal efficiency.

As indicated in Figure 7a, HRT has as linear effect of VS removal efficiency. Nevertheless, the effect is minimal. As HRT increases, the VS reduction increases. With longer retention time in the digester, more organic matter can be metabolized by the microorganisms, reducing the VS content at the outlet.



(a) (b) (c) (d)

Figure 7. 3D response surface plot on VS removal efficiency: (**a**) Combined effect of HRT and water: feedstock ratio; (**b**) Combined effect of HRT and POME:FW ratio; (**c**) Combined effect of recycle ratio and water:feedstock ratio; (**d**) Combined effect of water:feedstock ratio and POME:FW ratio.

The highest VS reduction can be observed when the water:feedstock ratio is 1 and the HRT is 40 days, as shown in Figure 7b. VS removal efficiency increases as water content increases [14]. The degradation of VS is enhanced as water helps to solubilize the degradable organic matter [51]. The addition of water solubilizes organic material, making it more assessable by microorganisms. Furthermore, the VS concentration introduced into the digester is reduced with the addition of water.

The recycle ratio has a linear effect on VS removal efficiency. The VS removal efficiency reduces when recycle ratio increases, as observed in Figure 7c. This occurs as the increased organic matter are not fully degraded, thus lowering the VS destruction rate.

The effect of co-substrate addition has a linear effect on the VS removal efficiency, as illustrated in Figure 7d. As the organic content is lower when POME:FW ratio is high, less organic matters are available to be metabolized by the microorganisms when compared to ratio of 0. Evidently, VS reduction is higher without the addition of co-substrate. The highest VS reduction is observed when the water:feedstock ratio is 1 and no co-substrate addition.

In summary, the impact of moisture content in the feedstock has the highest impact as observed. Other parameters have a lesser effect on the VS reduction.

3.4. Optimization Using RSM

Table 5 shows the optimized value obtained from Design-Expert Software, with desirability of 1. Here, the specification for methane flow is to 'maximize' and the removal efficiencies are set to 'in range'. Methane flow is maximized as it is the major revenue for the plant. Furthermore, the removal efficiencies are set within range as further COD and VS reduction can occur at wastewater stabilization part. The HRT obtained is around 37.2 days. This helps to generate more biogas as well as ensuring complete degradation of the organic matter. Furthermore, the recycle ratio is 0.381. A low recycle ratio is preferred to prevent overloading into the digester which results in decreased digester performance and efficiency. Furthermore, water to feedstock ratio is low as water addition reduces methane production. As it aids in VS reduction, 681.34 kg/h of water is added into the AD process. POME:FW ratio obtained is low, 0.004. FW required is 24,901.00 kg/h with POME of 99.22 kg/h. This is because the organic matter of POME is low due to high moisture content.

Table 5. Optimization results.

Factors	Value
HRT	37.2
Recycle ratio	0.381
Water: Feedstock ratio	0.027
POME: FW ratio	0.004

Table 6 compares the improvements obtained. The base case is simulated with HRT of 10 days (minimum value), recycle ratio of 0, water:feedstock ratio of 0 and POME:FW ratio of 0. As observed, the methane flow from the digester is lower due to the incomplete degradation of organic matter. An improvement of 34.5% is achieved in the optimized case, increasing the revenue. Methane yield is enhanced due to the longer retention time and the recycling of sludge back into digester. Subsequently, a lower methane yield, 0.25 L CH_4/g COD removed is obtained from base case simulation. The methane yield can be improved by 16.9% from optimization of parameters involved. The COD removal efficiency is also lower for the base case as less organic matter is degraded and converted into biogas. Furthermore, an improvement of 13.8% of VS removal efficiency is achieved. This can be attributed to the addition of water.

Table 6. Comparison between base case and optimized case.

Parameters	Base Case	Optimized Case	Improvements (%)
Methane flow (kg/h)	979.06	1495.86	34.5
Methane yield (L CH_4/g COD removed)	0.25	0.30	16.9
COD removal efficiency (%)	70.9	81.5	12.9
VS removal efficiency (%)	59.4	68.9	13.8

For AD of FW, 0.254 to 0.282 L of methane is produced from 1 g of COD destroyed [46]. Here, the methane yield is calculated to be 0.30 L CH_4/g COD removed for optimized case, comparable to the literature value stated. The methane yield obtained in this simulation is higher as POME and water is added to the digester. The addition of water helps to solubilizes organic material. POME which has a higher biodegradability also contributes to a higher methane yield. Based on experiments conducted by Yi et al. [47] the VS removal efficiency range from 65 to 70%. The value obtained from simulation is within the range.

The composition of the biogas generated is displayed in Table 7. The molar compositions obtained for each component are complementary to the values mentioned previously. Thus, the simulation of AD process is deemed appropriate. After upgrading, the methane molar composition is increased to 63.61%. The concentration of H_2S meets the requirement which is below 500 ppm$_v$. The removal efficiency of H_2S biotrickling filter is 99.75%. 98.92% of water is condensed out in the dehumidifier.

Table 7. Composition of biogas.

Component	From AD		Upgraded	
	Mass Flowrate (kg/h)	Molar Composition (%)	Mass Flowrate (kg/h)	Molar Composition (%)
Methane	1495.86	60.92	1495.86	63.61
CO_2	2350.34	34.81	2350.34	36.35
H_2S	39.10	0.75	0.00	0.00
Water	97.28	3.52	1.05	0.04
Total	3982.58	100.00	3847.25	100.00

Table 8 shows the COD, BOD_5 and TS of the treated water stream. Thus, it meets the limit of Standard A.

Table 8. COD, BOD_5 and TS for treated wastewater.

Parameter	Value (mg/L)
COD	14.1
BOD_5	8.8
TS	10.4

3.5. Economic Analysis

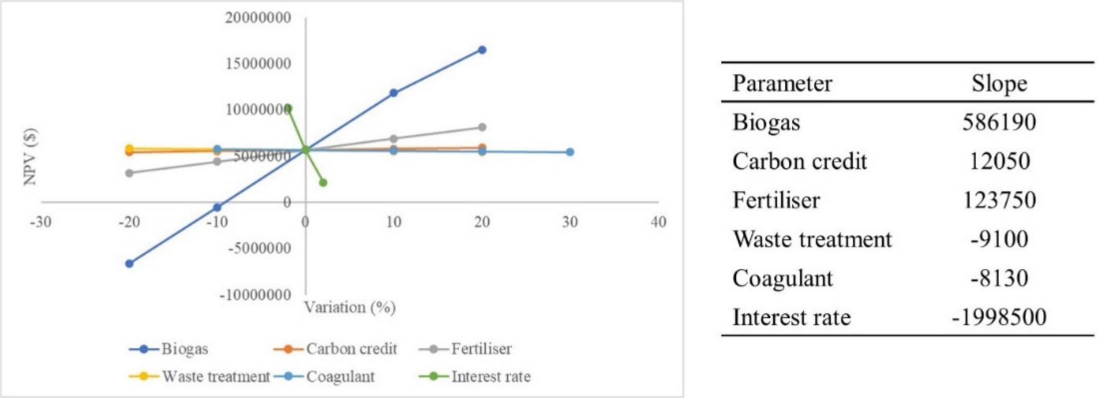
Economic analysis is conducted using 'Economic Evaluation' function in SuperPro Designer and displayed in Table 9. The plant is set to operate for 8000 h per annum. Typically, the lifespan of AD plants is around 20 years [52]. Both feedstocks are considered to incur zero charges on raw material cost (considered waste). The revenues are from upgraded biogas, carbon credit and fertilizer. The pricing for raw material, revenue and waste treatment are listed in Table A5 whereas the price for each equipment is listed in Table A6.

Table 9. Economic evaluation.

Aspect	Unit	Value
Total capital investment	$	19,396,000
Operating cost	$/yr	11,070,000
Total revenues	$/yr	13,510,000
Gross margin	%	18.06
Return of investment (ROI)	%	16.30
Payback time	year	6.14
IRR (IRR) (after taxes)	%	10.55
NPV (at 7.0% interest)	$	5,680,000

The total capital investment required in this project is $ 19,396,000. The gross margin evaluates how production costs affect revenue. A gross margin of 18.06% indicates that the company retain $ 18.06 from each $ 100 generated. The profitability of the project is also investigated using ROI. The ROI for this project is 16.30%, which indicates an attractive return rate. The payback period is 6.14 years. This is where the production cost is equivalent to the income, recovering the initial investment. IRR is 10.55%. An acceptable value is greater than 9%. This indicates that the project is worth continuing and proceeding to the next planning stage [53]. According to Towler and Sinnott [54], NPV is the total present value of future cash flow. A positive NPV provides indication that the project is feasible and profitable. Therefore, this project is deemed feasible and expected to generate great revenues and simultaneously achieve sustainability in terms of energy and environmental aspects.

Sensitivity analysis is useful in identifying the sensitive optimization parameter that has a significant impact on the viability of the plant operation parameters [55]. In this work, the sensitivity analysis has been carried out to investigate the impact of uncertainties of parameters on the results of the optimization as illustrated in Figure 8. The range of variation is as follows, revenues and waste treatment with ±20%, coagulant–10 to +30% and interest rate with ±2% [54]. A steeper slope indicates that the parameter greatly affects the NPV. A positive slope indicates parameters that are revenue whereas negative value indicates expenditure in the operation. As biogas is the main product, the variation in price has a noticeable effect on the NPV. This signifies biogas as the major contributor to the overall profit gain. The impact of carbon credit and fertilizer are minimal. Therefore, one of the few key aspects in reviewing the degree of feasibility and profitability of food waste to biogas production is the market value of biogas. For expenditure, interest rate has the most impact on NPV.



Parameter	Slope
Biogas	586190
Carbon credit	12050
Fertiliser	123750
Waste treatment	-9100
Coagulant	-8130
Interest rate	-1998500

Figure 8. Graph of variation of different parameters versus NPV.

3.6. Limitations and Improvements

With a higher total solids content, the viscosity of digestate increases, resulting in increased mass transfer resistance for diffusion of gases. The limitation of this simulation is the hydrodynamic conditions and parameters of digestate in the digester is unknown such as the viscosity and pH. However, mixing can be incorporated in experiments or digester to overcome mass transfer resistance.

According Selaman and Wid [56], the total TS and VS reduction is the best with POME:FW ratio of 3:7. A balance of sodium and potassium ions helps to enhance digestion process. Sodium ions are required as an energy source to microorganism whereas potassium ions stabilize polyphosphate compounds.

As OLR increases beyond the acceptable limit (increased recycle ratio), this upsets the digestion process. This leads to production and accumulation of volatile fatty acids. The acidic pH surrounding is not optimal for bacterial activities. However, as the recycle ratio increases, the methane production increases in this simulation as volatile acid production are not accounted for in the simulation.

Pre-treatment is also crucial in increasing biogas production. With size reduction, greater surface area available for contact with microorganisms. The biogas production is enhanced by 21% when the particle size is reduced from 100 to 10 mm [57]. Thermal pre-treatment enhances the biodegradability of the organic matter. However, the effect of pre-treatment on methane production is not visible from simulation.

Experimental works should also be conducted. This is to study the effect of pre-treatment in methane production to increase the reliability of results. Moreover, other parameters such as mixing rate, pH, carbon to nitrogen ratio and inoculum to substrate ratio should also be investigated. These parameters greatly affect the digestion process as well. Experimental results can help to validate the simulation results as well [58].

4. Conclusions

A complete AD process is successfully simulated with SuperPro Designer. H_2S is removed to meet a specification of below 500 ppm. Wastewater stabilization was also carried out to reduce COD, BOD_5 and TS in order to meet Standard A. Furthermore, fertilizer from sludge drying can be sold for extra income. Following optimization using Design-Expert, biogas production at mesophilic condition is maximized with an HRT of 37.2 days, recycle ratio of 0.381, water:feedstock ratio of 0.027 and POME:FW ratio of 0.004. The methane generated is 1495.86 kg/h, COD removal efficiency of 81.5% and VS removal efficiency of 68.9% at the anaerobic digester. A methane yield is 0.30 L CH_4/g COD removed, comparable with literature value obtained. Furthermore, VS removal efficiency is also within range reported in literature. Furthermore, an improvement of 34.5% and 16.9% is observed for methane flow and methane yield as compared to the base case. From economic studies, the revenue generated from biogas, carbon credit and fertilizer amount to $ 13,510,000. The ROI is high, indicating an attractive return rate. The payback period for this project is 6.14 years with NPV of $ 5,680,000. The project is deemed feasible and profitable. Studying the effect of these parameters helps keep AD process stable, maximizing methane yield. This enables advancement and maturation of technology for large scale production and aids in the transition towards bioenergy to promote sustainability. This reduces the dependency on natural gas and shifts to renewable energy generation in Malaysia.

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Appendix A

Equations for hydrogen sulfide removal.

$$H_2S + \frac{1}{2}O_2 \rightarrow S + H_2O \tag{A1}$$

$$H_2S + 2O_2 \rightarrow SO_4^{2-} + 2H^+ \tag{A2}$$

Table A1. Experimental design and results for Design-Expert.

Std	Run	A	B	C	D	Methane Flow	COD Removal Efficiency	VS Removal Efficiency
		days	-	-	-	kg/h	%	%
28	1	25	0.5	0.5	0.5	1175.78	80.9658	67.2347
24	2	25	1	0.5	1	1034.44	76.4242	61.6640
4	3	40	1	0.5	0.5	1218.72	78.3199	65.4878
6	4	25	0.5	1	0	1276.85	81.7124	72.5177
5	5	25	0.5	0	0	1453.12	79.9111	67.5468
13	6	25	0	0	0.5	1207.76	81.2772	64.2757
21	7	25	0	0.5	0	1307.79	82.3110	71.4201
27	8	25	0.5	0.5	0.5	1175.78	80.9695	67.2457
2	9	40	0	0.5	0.5	1184.23	83.6612	69.1767
11	10	10	0.5	0.5	1	949.43	78.2078	63.0579
14	11	25	1	0	0.5	1242.37	76.0147	61.4564
26	12	25	0.5	0.5	0.5	1175.78	80.9656	67.2339
12	13	40	0.5	0.5	1	1035.81	80.1988	63.6074
19	14	10	0.5	1	0.5	1009.83	80.2276	69.2727
3	15	10	1	0.5	0.5	1104.21	76.1304	64.1569
16	16	25	1	1	0.5	1156.62	79.4408	68.2552
20	17	40	0.5	1	0.5	1158.07	82.8689	70.7427
8	18	25	0.5	1	1	986.288	81.7494	67.8420
10	19	40	0.5	0.5	0	1429.72	81.9599	71.1286
9 *	20	10	0.5	0.5	0	1005.11	73.9917	64.7882
18	21	40	0.5	0	0.5	1247.97	79.6335	63.2548
17	22	10	0.5	0	0.5	1119.56	76.5432	61.2736
29	23	25	0.5	0.5	0.5	1175.78	80.9694	67.2454
15 *	24	25	0	1	0.5	1105.94	84.5753	72.5403
1	25	10	0	0.5	0.5	1016.06	80.1391	67.0020
23	26	25	0	0.5	1	1004.27	82.2623	65.2784
7	27	25	0.5	0	1	1054.48	77.2327	57.6747
22	28	25	1	0.5	0	1408.64	78.5930	68.6410
25	29	25	0.5	0.5	0.5	1175.78	80.9682	67.2417

* Outlier and excluded from analysis.

Table A2. ANOVA results for methane flow.

Source	Sum of Squares	df	Mean Square	F-Value	p-Value	
Model	4.66×10^{05}	14	33,273.6	1124.95	<0.0001	significant
A	49,077.78	1	49,077.78	1659.28	<0.0001	
B	10,106.16	1	10,106.16	341.68	<0.0001	
C	31,470.47	1	31,470.47	1063.99	<0.0001	
D	2.88×10^{05}	1	2.88×10^{05}	9734.52	<0.0001	
AB	719.95	1	719.95	24.34	0.0003	
AC	98.3	1	98.3	3.32	0.0933	
AD*	1912.12	1	1912.12	64.65	<0.0001	
BC	552.29	1	552.29	18.67	0.001	
BD	1248.67	1	1248.67	42.22	<0.0001	
CD	2920.18	1	2920.18	98.73	<0.0001	
A^2	7721.4	1	7721.4	261.05	<0.0001	
B^2	273.2	1	273.2	9.24	0.0103	
C^2	69.12	1	69.12	2.34	0.1523	
D^2	2503.77	1	2503.77	84.65	<0.0001	

SD = 5.44, CV% = 0.47, R^2 = 0.9992, Adjusted R^2 = 0.9984, Predicted R^2 = 0.9937, Adequate precision = 123.34.

AD* to differentiate with anaerobic digestion (AD).

Table A3. ANOVA results for COD removal efficiency.

Source	Sum of Squares	df	Mean Square	F-Value	*p*-Value	
Model	119.86	14	8.56	498.66	<0.0001	significant
A	19.89	1	19.89	1158.42	<0.0001	
B	56.56	1	56.56	3294.39	<0.0001	
C	25.68	1	25.68	1495.79	<0.0001	
D	3.21	1	3.21	187.07	<0.0001	
AB	0.444	1	0.444	25.86	0.0003	
AC	0.0504	1	0.0504	2.93	0.1124	
AD*	0.3728	1	0.3728	21.71	0.0006	
BC	0.0967	1	0.0967	5.63	0.0352	
BD	1.12	1	1.12	65.45	<0.0001	
CD	1.84	1	1.84	107.37	<0.0001	
A^2	3.81	1	3.81	222.08	<0.0001	
B^2	1.71	1	1.71	99.76	<0.0001	
C^2	0.5003	1	0.5003	29.14	0.0002	
D^2	1.35	1	1.35	78.89	<0.0001	

SD = 0.13, CV% = 0.16, R^2 = 0.9983, Adjusted R^2 = 0.9963, Predicted R^2 = 0.9861, Adequate precision = 79.87.

Table A4. ANOVA results for VS removal efficiency.

Source	Sum of Squares	df	Mean Square	F-Value	*p*-Value	
Model	324.64	14	23.19	488.93	<0.0001	significant
A	7.02	1	7.02	148.02	<0.0001	
B	26.49	1	26.49	558.46	<0.0001	
C	141.23	1	141.23	2977.95	<0.0001	
D	114.1	1	114.1	2405.87	<0.0001	
AB	0.178	1	0.178	3.75	0.0766	
AC	0.0653	1	0.0653	1.38	0.2633	
AD*	0.6361	1	0.6361	13.41	0.0033	
BC	0.1635	1	0.1635	3.45	0.088	
BD	0.1744	1	0.1744	3.68	0.0793	
CD	6.75	1	6.75	142.34	<0.0001	
A^2	1.43	1	1.43	30.12	0.0001	
B^2	0.2938	1	0.2938	6.19	0.0285	
C^2	1.79	1	1.79	37.83	<0.0001	
D^2	0.2923	1	0.2923	6.16	0.0288	

SD = 0.22, CV% = 0.33, R^2 = 0.9982, Adjusted R^2 = 0.9962, Predicted R^2 = 0.9858, Adequate precision = 88.23.

Table A5. Price of raw material, revenue and waste treatment.

Aspect	Component	Unit	Cost	Reference
Raw material	Coagulant	$/ton	450	[32]
Revenue	Biogas	$/kg	0.360	[59]
	Carbon credit		0.007	[60]
	Dried sludge (fertilizer)		0.132 *	[61]
Waste treatment	BTF effluent Dehumidifier effluent S-109 Washout 1 Washout 2	$/ton	1.5	[54]

* 2 Units.

Table A6. Breakdown of equipment cost.

Equipment	Capacity	Capacity	Unit Cost ($)	Reference
Grinder (GR-101)	Size	25,000.20 kg/h	20,000	[62]
Sterilizer (ST-101)	Throughput	24,788.66 L/h	860,000	Default value from SuperPro Designer
Blower (M-101)	Throughput	3,779,280.19 L/h	7000	
Dehumidifier (HX-101)	Condensation area	7.82 m^2	45,000	
Sludge drying (SLDR-101)	Evaporative capacity	2622.01 kg/h	42,000	
Unlisted equipment	-	-	367,000	
Anaerobic digester (AD-101) *	Volume	13,220,377.56 L	823,000	[54]
Aerobic digester (AB-101)	Volume	1,097,822.60 L	268,000	
Biotrickling filtration (TF-101)	Cross sectional-area	0.212 m^2	113,000	[63]
Primary clarifier (CL-101)	Surface area	60.51 m^2	72,000	
Secondary clarifier (CL-102)	Surface area	56.55 m^2	72,000	
GM filtration (GMF-101)	Volume	0.41 L	13,000	
Belt filtration (BF-101) *	Width	2.38 m	75,000	

* 2 Units.

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