

Design and Optimisation of Wastewater Treatment Plant for the Poultry Industry

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Abstract The objective of this study is to optimise the wastewater treatment plant of poultry industry. The optimisation of simulation model was done using the SuperPRO designer as simulator. The performance of the wastewater treatment plant for the poultry industry has improved significantly at the minimum cost. The COD value reduced from 133 mg/L to 0.05 mg/L at the discharge stream 1 and 73.7 mg/L for discharge stream 2. In addition, the BOD5 value reduced from 66.7 mg/L to 0.03 mg/L at the discharge stream 1 and 47.1 mg/L at the discharge stream 2. Further to this, the TSS reduced from 33.3 mg/L to 0.0 mg/L at the discharge stream 1 and 1.69 mg/L at the discharge stream 2. Oil and grease also reduced from 3.3 mg/L to 0.024 mg/L at the discharge stream 1 and 18.7 mg/L at the discharge stream 2. The existing model and system can improve the wastewater treatment plant of poultry industry.

1 Introduction

The government has set the discharge standards of effluents in Environmental Quality (Industrial and Sewage Effluents) Regulations 2009. The values of total suspended solids (TSS), COD, BOD5, nitrate nitrogen and oil and grease should be less than or equal to 100, 200, 50, 50, and 10 mg/L respectively to reach standard B. Those should be less than or equal to 50, 120, 20, 20 and 5 mg/L respectively to reach standard A (Department of Environment, 2009).

Plants built before 2009 need to comply with the rules and regulation set by the DOE. A poultry industry with a wastewater treatment plant was selected in this study. The existing wastewater treatment plant was designed to discharge 72 m³/day of effluent. The TSS, COD, BOD5, oil and grease set for the designed are 33.3, 133, 66.7 and 3.3 mg/L, respectively. The plant consists of an oil and grease separation, an equalisation, a flocculation tank, a coagulation tank, a dissolved air floatation unit, an activated sludge reactor, a clarifier and a filter press. In this process, it consists of a recycle stream connected from the filter press to the equalisation tank. The existing plant efficiency has high potential to improve by re-designing the process by optimising the recycle ration.

Will the discharge stream reduced or performed better after optimisation and what is the best design to optimise the process? A simulation model was established to improve the performance of the wastewater treatment plant. The poultry wastewater treatment system was simulated through the SuperPro

Designer, and the performance was improved based on the existing wastewater treatment plant shown in Figure 1 with purchasing of an activated sludge reactor, a clarifier, a storage tank and a belt filter only but remaining the rest of the plant.

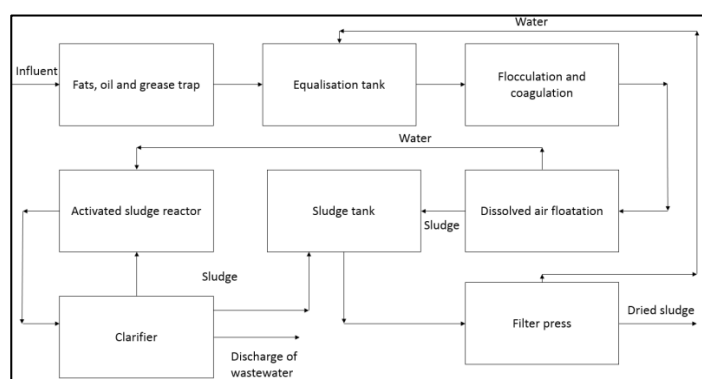


Figure 1. Flow diagram of the existing wastewater treatment plant

2 Poultry Wastewater Treatment Design

2.1 Wastewater treatment with recycling

SuperPro Designer has been applied for design, process analysis, evaluation and optimisation of the poultry wastewater treatment. Since in reality, the average flow to the wastewater treatment is 72 m³/day and the operation time is eight hours per day. Thus, in the

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simulation modelling, the average flow of the influent to the treatment process flowrate was set as 3.0 m³/h and operated for 24 hour per day as the process operation mode was continuous. A minor modification based on the exiting model and the real wastewater treatment plan where the water from the belt filtration is not recycled to the equalisation tank. This stream does not help in reducing the environmental properties, but it requires larger operating cost and larger equipment.

2.2 Influent stream and mass balance

The input stream to the wastewater treatment plant was supplied at 30°C and atmospheric pressure. It consists of sludge, ammonia, water and carbon dioxide. In this case, the average flowrate of the influent is 3.0 m³/h. The components in influent stream, their flow rates and concentrations are shown in Table 1.

In the mass balance calculation, different recycle ratio was set to check the environmental properties in the discharge streams. The mass in was the sum of mass of influent, polymer, air to DAF and water to belt filter. For mass out, it was the sum of mass of oil and grease, S-104, discharge stream 1, discharge stream 2 and sludge.

Table 1. Details of the influent stream

Components	Flowrate (kg/h)	Mass Composition (%)	Concentration (kg/m ³)
Carbon Dioxide	0.1400	0.0051	0.0481
Ammonia	0.0600	0.0021	0.0198
Dom Waste	0.1500	0.0052	0.0491
Water	2830	99.95	943.5
FSS	0.0300	0.0010	0.0094
TDS	0.8700	0.0306	0.2888
X-VSS-h	0.0300	0.0010	0.0094
X-VSS-n	0.0300	0.0010	0.0094
X-VSS-i	0.0200	0.0006	0.0057

2.3 Components registered

Before starting the simulation, the components in database were added and those not in the database was registered with user defined components (Table 2).

Table 2. Component variables registered in the simulation

Variables	User Defined	Definition
Carbon Dioxide	No	CO ₂ or dissolved in the form of HCO ₃ or/and H ₂ CO ₃
Ammonia	No	NH ₃ or dissolved NH ₄
DomWaste	Yes	Bio-degradable waste
Water	No	Pure water
Oxygen	No	Oxygen diffused from aeration/air supplied
Nitrogen	No	Product from denitrification and air supplied
FSS	Yes	Fixed Suspended solid (non-degradable)
NO ₃	Yes	Nitrate in whole nitrification
NO ₂	Yes	Nitrite in partial nitrification
TDS	Yes	Non-biodegradable dissolved solids
X-VSS-h	Yes	Active heterotrophic biomass used in denitrification
X-VSS-n	Yes	Active nitrifies autotrophic biomass
X-VSS-i	Yes	Inert biomass represents biomass decay

2.4 Description of units and discharge streams

Grit Chamber (GB – 101): The grit chamber removes part of the fixed suspended solids including fats, oil and grease from the influent. The grit chamber removes 70% of the solids.

Equalisation tank (EQ - 101): The equalisation tank functions like a ‘buffer’. Even there is high flow fluctuation of the influent, the equalisation will still provide consist flow to the downstream treatment process. As the equalisation tank is in open air, there is no vented stream for the gases. An assumption is also

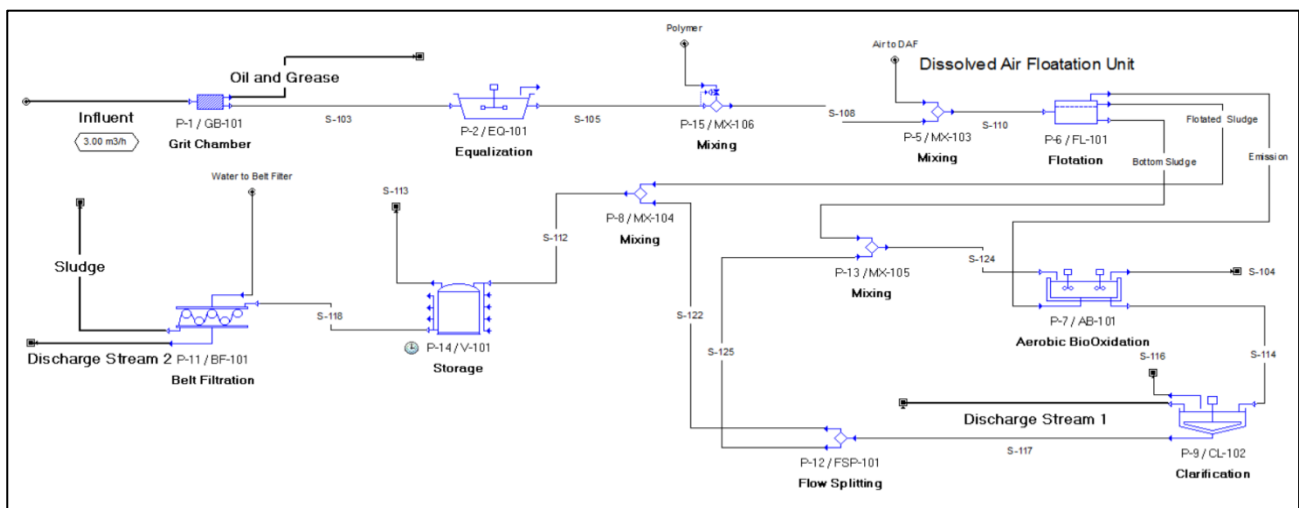


Figure 2. The flowsheet of the poultry wastewater treatment

made that no reaction occurs in the equalisation tank (Auto Garment, 2018).

Mixer (MX - 106): The mixer is to mix the wastewater and polymer for flocculation and coagulation. This represents a simplified version of flocculation and coagulation unit.

Mixer (MX - 103): It represents part of the simplified dissolved air flotation unit. The mixer is to mix the wastewater and air supplied which can lift the suspended matters to the surface in the dissolved air flotation unit.

Flotation Unit (FL - 101): It represents part of the simplified dissolved air flotation (DAF) tank. This allows three layers to be separated; namely, top sludge, vented gases, and bottom sludge as shown in Figure 2. It is the demonstration of the results done DAF tank.

Mixer (MX - 105): The mixer is to mix the bottom sludge from DAF tank and the recycle stream from clarifier after the splitter.

Aerobic Reactor (AB-101): It represents the activated sludge reactor. The reactor converts ammonia into nitrite or nitrate. The vented gas from the flotation unit is being supplied that allows the reactions to occur for the treatment. Excessive nitrogen, oxygen and carbon dioxide are then emitted from the reactor.

Clarifier (CL -102): It clarifies the stream of 90% of sludge. After clarification, the wastewater is discharged, and small amount of carbon dioxide is emitted.

Flow Splitting (FSP - 101): The flow is then split two streams; one to recycle into the sludge reactor, one to storage tank. The splitting ratio to the bottom is equal to the recycle ratio to the activated sludge reactor, which plays an important role in optimising the wastewater treatment.

Mixer (MX - 104): The mixer is to mix the floated sludge from DAF tank and part of the downstream from clarifier.

Storage Tank (V - 101): The storage tank is whereby the floated sludge from DAF tank and the downstream from clarifier are collected.

Belt Filter (BF - 101): It is to separate the sludge and the liquid phase. Furthermore, a stream of water is used to help the separation. The sludge will be collected by agencies approved by Department of Environment, Malaysia.

Discharge Stream 1 and 2: They make up the effluent from the wastewater treatment plant. They are discharged into river directly. The concentration of each component were assessed and analysed. It was compared with the permissible values of discharge standards provided by the Environmental Quality Act 2009, Malaysia.

2.5 Reactions in the activated sludge reactor

There are five reactions occurred in the activated sludge reactor viz. autotrophic biomass decay reaction, heterotrophic biomass decay reaction, denitrification, domwaste degradation and full nitrification are shown in Table 3, 4, 5, 6 and 7, respectively. These reactions are described as follows with their mass-based stoichiometry (Waheed, 2010):

Autotrophic Biomass (X-VSS-n) Decay Reaction:
 $X-VSS-n + O_2 \rightarrow NH_3 + CO_2 + H_2O + X-VSS-i$

Table 3. Autotrophic Biomass (X-VSS-n) Decay Reaction

Component	X-VSS-n	O ₂	NH ₃	CO ₂	H ₂ O	X-VSS-i
Mass	1.05	1.15	0.1	1.45	0.45	0.20
Stoichiometry/g						

Heterotrophic Biomass (X-VSS-h) Decay Reaction
 $X-VSS-h + O_2 \rightarrow NH_3 + CO_2 + H_2O + X-VSS-i$

Table 4. Heterotrophic Biomass (X-VSS-h) Decay Reaction

Component	X-VSS-h	O ₂	NH ₃	CO ₂	H ₂ O	X-VSS-i
Mass	1.05	1.15	0.1	1.45	0.45	0.20
Stoichiometry/g						

Denitrification

$DomWaste + NO_3 \rightarrow CO_2 + N_2 + H_2O + X-VSS-h$

Table 5. Denitrification

Component	Dom Waste	NO ₃	CO ₂	N ₂	H ₂ O	X-VSS-h
Mass	34.6	108	48	17	61.4	16.2
Stoichiometry/g						

DomWaste Degradation

$DomWaste + NH_3 + O_2 \rightarrow X-VSS-h + H_2O + CO_2$

Table 6. DomWaste Degradation

Component	Dom Waste	NH ₃	O ₂	X-VSS-h	H ₂ O	CO ₂
Mass	1	0.1	1.4	0.8	0.8	0.9
Stoichiometry/g						

Full nitrification

$NH_3 + O_2 + CO_2 \rightarrow X-VSS-n + H_2O + NO_3$

Table 7. Full nitrification

Component	NH ₃	O ₂	CO ₂	X-VSS-n	H ₂ O	NO ₃
Mass	7.5	29.46	2.19	1.12	11.29	26.74
Stoichiometry/g						

3 Costing and Optimisation

The capital cost mainly consisted of the purchased cost of the active sludge reactor, the clarifier, the storage tank and the belt filter were investigated and analysed. Existing units like the grit chamber, the equalisation tank, the DAF tank were not considered as capital cost as these are existing units. The unit cost was estimated based on equation (1).

$$\alpha_2 = \alpha_1 \left(\frac{\beta_2}{\beta_1}\right)^\gamma \quad (1)$$

Where α is cost of equipment, β is size of equipment and γ is size exponents. The size exponents were 1.03, 0.6, 0.3 with respect to the clarifier tank, the sludge reactor and the storage tank, respectively (Donald, 1989). Similarly, equation (2), (3) and (4):

$$P_2 = P_1 \left(\frac{\beta_2}{\beta_1}\right)^\gamma \quad (2)$$

Where P is power of equipment. The power of the rest system was assumed to be 1.0 kWh. Assumption made were the operation duration set at 350 days per year, and 24 hour per day. The total amount of wastewater calculated based on the flowrate of influent of 3.0 m³/h.

$$\theta = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (3)$$

Where θ is the annualised factor, i is the interest rate per year, and n is the number of years of the duration to borrow money.

$$C_F = f_I \sum_i C_{E,i} \quad (4)$$

Where C_F is the installed capital cost, f_I is the overall installation factor which is 5.8 in this case and $C_{E,i}$ is the capital cost for the equipment i (Smith, 2005). So, the total annualised cost, C_T is shown in equation (5).

$$C_T = C_F \theta \quad (5)$$

By assuming the duration to return money to be 30 years, the interest rate is 7.4% taken from HSBC official website (Business.hsbc.uk, 2019). For maintenance cost, the annual maintenance was calculated by multiplying a maintenance factor 5% with the capital cost. Then, the total maintenance obtained by multiplying the number of years.

4 Results and Discussion

4.1. Performance of Mainly Influenced Equipment

4.1.1 Activated sludge reactor

The reactions occurred in the activated sludge tank to degrade the biomass. The gases vented from the DAF tank reacted as reactants in the reactor including ammonia, carbon dioxide and oxygen. Table 8 shows that after passing through the activated sludge reactor, After reaction, the oil and grease, COD, BOD₅ and TSS decreased from 5.63 to 0.29 ppm, 847 to 109 ppm, 461 to 72.3 ppm and 662 to 91.0 ppm, respectively from recycle ratio of 95% to 0%. The changes of oil and grease after treatment was ranged from 1.6 to 3.0%, the changes were too small, which is negligible. For the COD and BOD₅ changes were not significantly different when the recycle ratio was set from 0 to 40%, where total changes below 6%. However, the TSS value increased significantly for recycle ratio ranged from 0 to 80% which is as high as 25%.

4.1.2 Clarifier tank

The clarifier tank separates the solids and liquid phase. The liquid is discharged, and the solids were sent to the storage tank or/and the activated storage tank. Table 10 shows the removal rate of Oil and Grease, COD, BOD₅ and TSS at recycle ranged from 0% to 95%. The initial concentration of Oil and Grease ranged from 0.3 to 5.72. After the clarifier separation process, it was reduced significantly to around 0.02 to 0.9 ppm. Similar trends can be observed from the COD, BOD₅ and TSS. These few parameters initial concentrations were ranged from 109 to 847 ppm, 106 to 461 ppm, 9.0 to 662 ppm, respectively at recycle ratio set from 0 to 95%. The clarifier tank can reduce the Oil and Grease, COD, BOD₅ and TSS value close to 99% at different recycle ratio. This discharge stream met the permissible values of discharge standards set by the Environmental Quality Act 2009, Malaysia.

Table 8. Oil and Grease, COD, BOD₅ and TSS at the inlet and outlet of the activated sludge reactor

Recycle Ratio/%	Inlet of the Reactor (S-124)				Outlet of the Reactor (S-114)			
	Oil and Grease	COD	BOD ₅	TSS	Oil and Grease	COD	BOD ₅	TSS
95	5.72	927	518	646	5.63	847	461	662
90	2.89	590	336	379	2.84	522	285	405
80	1.46	350	206	182	1.43	291	161	213
70	0.980	297	188	78.9	0.950	258	158	98.9
60	0.740	263	173	30.6	0.720	244	159	36.8
50	0.590	218	145	20.1	0.570	204	135	23.5
40	0.500	185	123	15.2	0.480	174	115	17.6
30	0.430	160	107	12.4	0.410	151	100	14.1
20	0.370	141	94.2	10.5	0.360	134	88.9	11.9
10	0.330	126	84.3	9.10	0.320	120	79.7	10.3
0	0.300	114	76.3	8.10	0.290	109	72.3	9.10

Table 9. Oil and Grease, COD, BOD₅ and TSS at the inlet and outlet of the clarifier tank

Recycle Ratio/%	Inlet of the Clarifier Tank (S-114)				Outlet of the Clarifier Tank (Discharge stream 1)			
	Oil and Grease/ppm	COD /ppm	BOD ₅ /ppm	TSS /ppm	Oil and Grease/ppm	COD /ppm	BOD ₅ /ppm	TSS /ppm
95	5.63	847	461	662	0.006	0.900	0.490	0.703
90	2.84	522	285	405	0.003	0.540	0.290	0.419
80	1.43	291	161	213	0.001	0.280	0.150	0.220
70	0.950	258	158	99.0	0.001	0.140	0.080	0.102
60	0.720	244	159	37.0	0.001	0.070	0.040	0.038
50	0.570	204	135	24.0	0.001	0.050	0.030	0.024
40	0.480	174	115	18.0	0.001	0.040	0.020	0.018
30	0.410	151	100	14.0	N.A.	0.030	0.020	0.015
20	0.360	134	89.0	12.0	N.A.	0.030	0.020	0.012
10	0.320	120	80.0	10.0	N.A.	0.020	0.010	0.011
0	0.300	109	106	9.00	N.A.	0.020	0.010	0.009

*N.A. Not applicable as it is too close to zero.

4.1.3 Belt filter

A minor modification was made in the exiting design model compared to the real wastewater treatment plant where the water from the belt filtration was not recycled to the equalisation tank. It was found that water discharged at this stream does not help in reducing the environmental properties but required larger operating cost and equipment. Referring to Table 10, it shows the discharge properties of COD, BOD₅, oil and grease, TSS and (NO₃/NO₂) when the recycle ratio changed from 0 to 95%. The setting of recycle ratio above 50% is not acceptable as the BOD₅ exceeded the parameter limits of effluent of Standard B set by the Malaysia Environment Quality (Sewage and Industrial Effluents) Regulations. The recycle ratio below 60% is acceptable as the BOD₅ value ranged from 26.5 to 47.1 from 0 to 50%. Further to this, the COD limit set by the local authority is less than 100 ppm for standard B. Therefore, any settings above the recycle ratio of 70% exceed the limit as it is ranged

from 105 to 230 ppm from 80 to 95% recycle ratio. For oil and grease, all values below 10 ppm, therefore, it is acceptable. Detail flowrate of sludge and water to belt filter are shown in Appendix 1.

Table 10. Environment properties of the discharge streams for different recycle ratios

Recycle Ratio/%	Discharge Stream 2 (ppm)				
	COD	BOD ₅	Oil and Grease	TSS	(NO ₃ /NO ₂)
95	230	125	9.93	187	0.226
90	165	90.0	6.31	133	0.196
80	105	57.9	3.72	81.3	0.202
70	92.6	55.4	2.65	45.8	0.338
60	86.4	54.7	2.06	24.9	1.10
50	73.7	47.1	1.69	18.7	1.87
40	63.7	40.8	1.44	15.3	2.47
30	56.0	36.0	1.25	13.0	2.83
20	49.9	32.1	1.11	11.4	2.99
10	45.1	29.0	1.00	10.1	2.99
0	41.1	26.5	0.910	9.10	2.91

4.2 Economic Evaluation after optimisation

Clarifier tank, activated sludge reactor and storage tanks cost and sizes are shown in Table 11. The cost of a clarifier tank, activated sludge reactor and storage tank are around RM 80 k, RM 350 k and RM 9.0 k, respectively based on the calculated size based on different volume. Referring to the simulation results, the cost of treating wastewater per m³ of water based on the existing design reduced from RM 105/ m³ to RM 14.8/ m³ when the years to run reduced close to 10 years. The costs to treat ranged from RM 8/ m³ to RM 11/ m³ for the remaining years. This calculated annualised capital cost and operating cost including the sum of charge for the disposal of sludge, the oil and grease sent for landfill, the cost of annual polymer used for coagulation and flocculation, the annual labour cost, the annual electricity, and the water utility to the belt filter are shown in Table 12.

The recycle ratio affected the total annual cost. Figure 3 shows the changed of total cost at recycle ratio. The recycle ration increase slightly when the recycle ration set at 10%. Then, it decreased drastically from RM 140 thousand to around RM 134 thousand. It became constant when the recycle ratio ranged from 20 to 95%. This could be due to the change of the volume of the sludge storage tank. It decreased when more sludge discharged with the effluents and the tank become smaller. In addition, the production of the sludge from the belt filter and the water utility applied to the belt filtration decrease as recycle ratio increases and resulted in less cost spent in sending sludge to landfill and paying for water bill.

Table 11. Different volume and price of the influenced units at different recycle ratio

Recycle ratio/%	Clarifier Tank Volume / (m ³)	Cost for Clarifier Tank /RM thousand	Activated Sludge Reactor Volume / (m ³)	Cost for Activated Sludge Reactor /RM thousand	Storage Tank Volume / (m ³)	Cost for Storage Tank /RM thousand
95	6.75	79.4	12.6	348	0.84	4.17
90	6.74	79.2	12.5	346	1.46	4.92
80	6.72	79.0	12.4	345	2.7	5.92
70	6.7	78.7	12.4	345	3.92	6.62
60	6.68	78.5	12.4	344	5.14	7.18
50	6.66	78.2	12.3	343	6.34	7.65
40	6.64	78.0	12.3	343	7.54	8.06
30	6.62	77.8	12.2	342	8.73	8.42
20	6.6	77.5	12.2	341	9.92	8.75
10	6.59	77.4	12.1	341	11.1	9.05
0	6.57	77.1	12.1	340	12.27	9.32

Table 12. Cost of treating wastewater per m³ of water

Years to run	Installed Capital Cost /RM million	Total Maintenance Cost/RM thousand	Total Operating Cost/ RM million	Total Cost to Treat Wastewater/ RM	Total Amount of Wastewater to Treat/ m ³ thousand	Cost to Treat per Volume of Wastewater/ (RM/ m ³)
1	2.53	21.8	0.097	2.65	25.2	105
5	2.53	109	0.488	3.13	126	24.8
10	2.53	218	0.984	3.73	252	14.8
15	2.53	327	1.46	4.32	378	11.4
20	2.53	436	1.95	4.92	504	9.76
25	2.53	545	2.44	5.52	630	8.76
30	2.53	654	2.92	6.11	756	8.09

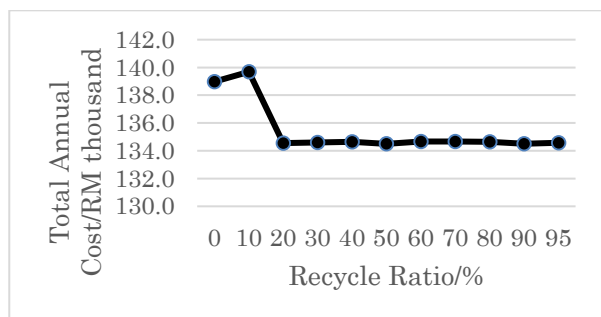


Figure 3. Total annual cost at different recycle ratio ranged from 0 to 100%

The lowest total annual cost was RM 135 thousand at 50% and the highest total annual cost was RM 140 thousands at 90%. Ensuring the discharge streams met discharge standards are important. Table 12 shows a

5 Conclusions

By optimising simulation model using the SuperPro Designer, performance of the wastewater treatment plant for the poultry industry can be predicted and the cost can be minimised. It can be seen from the huge reduction of COD from 133 mg/L to 0.049 mg/L for discharge stream 1 and 73.7 mg/L for discharge stream 2. A great reduction of BOD₅ from 66.7 mg/L to 0.003 mg/L for discharge stream 1 and 47.1 mg/L discharge stream 2 is also performed. TTS of 33.3 mg/L is reduced to 0.0 mg/L for discharge stream 1 and 1.69 mg/L for discharge stream 2. Oil and grease is also

simulation i with a recycle ratio of 50%. For the optimal recycle ratio of 50%, the environmental properties of the discharge streams met the discharge requirements compared to other settings showed in Table 10. The performance in terms of treating wastewater from the poultry industry with the minimum cost spent on operating and capital cost. The total capital cost of the units after recycle stream was about RM 31 thousand, the installed capital cost was RM 2.5 million after multiplying an installation factor of 5.8 (Smith, 2005). The cost of treating per volume of wastewater decreases significantly from year 1 to 10. It is mainly because the annual installed capital cost. The annual installed cost decreases slowly with time after Year 10. Hence, the cost of treating a cubic metre wastewater also declines gradually. After year 20, it becomes stable around RM 9.8 per cubic metre of industry wastewater.

reduced from 3.30 mg/L to 0.024 mg/L for discharge stream 1 and 18.7 mg/L for discharge stream 2. The discharge stream reduced or performed better after optimisation and the best design to optimise the process is setting the recycle ratio at 50%. The process performance of the wastewater treatment plant for the poultry industry is improved significantly at the minimum cost. The total capital cost of the units after recycle stream was about RM 31 thousand and the installed capital cost was RM 2.5 million. Simulation and optimisation have been done based on the existing wastewater treatment plant of poultry industry, and

good results have showed the practicability of the system.

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Appendix 1: The outlets of the wastewater treatment plant and the flowrate of water to the belt filter.

Recycle ratio/%	Production of Sludge/ (kg/hr)	Flowrate of Water to Belt Filter m ³ /hr	Discharge Stream 2 Flowrate m ³ /hr
95	0.499	3.025	0.009
90	0.544	3.666	0.013
80	0.653	4.394	0.023
70	0.761	5.126	0.032
60	0.862	5.804	0.041
50	0.932	6.275	0.05
40	0.993	6.69	0.059
30	1.05	7.069	0.068
20	1.10	7.421	0.076
10	1.15	7.749	0.085
0	1.20	8.057	0.094