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Treatment of Rubber Effluent with High Rate Algal Pond

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A pilot-plant study was conducted to determine the feasibility of high rate algal pond (HRAP) in the treatment of anaerobically digested rubber effluent. The results showed that the hydraulic retention time of six days is adequate to satisfactorily treat the rubber effluent. A design model for the system based on completely-mixed flow regime was found to be statistically better than that based on plug-flow condition. Considering the HRAP to exhibit completely-mixed flow regime, first order total nitrogen removal rate coefficient of 0.339 day^{-1} was obtained. Comparing the nitrogen removal rate of the HRAP with that of a facultative pond, the land area for the HRAP was estimated to be 60% smaller than that of the facultative pond.

Effluent treatment technology commonly used in the natural rubber processing industry is either the anaerobic/facultative ponding system or the oxidation ditch system[1]. The ponding system is preferred if land is available. The oxidation ditch is an alternative when pond space is limited. The oxidation ditch system which uses mechanical devices for aeration is however energy intensive[2].

High rate algal pond (HRAP) systems[3,4,5] for effluent treatment are usually less expensive to operate than the oxidation ditches because oxygen is supplied by algae rather than by mechanical devices. Furthermore, reinforced concrete often used in constructing 1.5 – 2.0 m deep oxidation ditches is probably not required because HRAP systems are shallower, only 0.2 – 0.6 m deep[4]. However, due to the shallower depth, land requirement by these algal systems is usually greater.

While effective effluent treatment may also be achieved in facultative ponds, the sub-optimal algal growth in these ponds requires a large land area for nitrogen removal. HRAP systems, instead, may use less land area than the facultative ponds, due to optimisation of algal growth in these ponds. In addition, the HRAP systems are in principle suited for producing protein-rich algal biomass because of the optimisation of algal growth in the systems.

For the above reasons, a pilot-scale study was conducted to determine the feasibility of the HRAP system in the treatment of rubber effluent. In this study, the HRAP system was used to treat anaerobically digested diluted field latex serum, the main source of effluent in block rubber processing.

DESCRIPTION AND OPERATION OF PILOT PLANT

In the pilot-plant study, a 5.5 m^3 anaerobic digester and a 1.65 m^3 HRAP system were used *(Figure 1)*. The raw effluent, diluted serum from formic acid coagulation of field latex, flowed by gravity at constant rate from a feed tank to the 1.6 m deep unmixed anaerobic digester. The anaerobic digester effluent then flowed by gravity into the HRAP. The HRAP, placed outdoors, was 0.35 m deep and its surface area was about 4.72 m^2. It was of a meandering channel design. Continuous mixing of the HRAP was provided to prevent thermal stratification and ensure that the algal cells receive maximum exposure to solar radiation. The mixing at constant rate was provided by a paddle wheel driven by a 0.75 kW motor with a speed reducer. The paddle wheel rotated at

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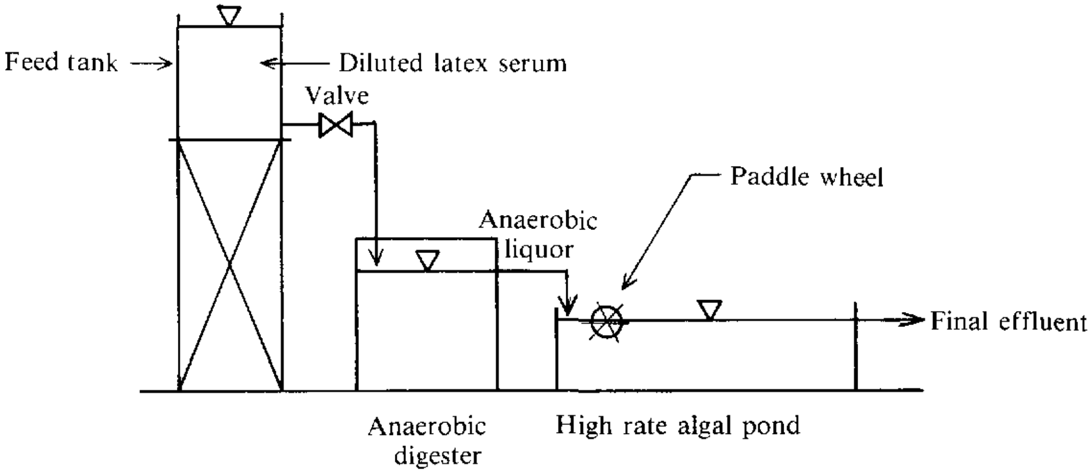
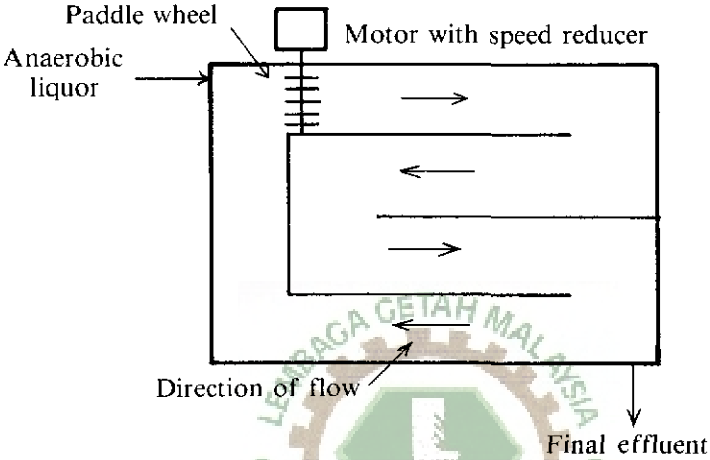


Schematic flow diagram of the pilot plant.



Top view of the high rate algal pond (not to scale).

Figure 1.

about nine revolutions per minute giving an average surface velocity in the channel of about 0.025 m/s.

The pilot plant was operated at various flow rates to give variable hydraulic retention times in the anaerobic digester and the HRAP *(Table 1)*. All other operating variables, such as, pond depth, mixing rate and mixing duration, were kept constant. Over the study period, averaged mean, minimum and maximum ambient temperatures were 26.7°C, 23.0°C and 32.3°C respectively[6].

TABLE 1. OPERATIONAL CONDITIONS FOR THE PILOT-PLANT STUDY

Run	Flow rate (litres/day)	Hydraulic retention time (days)	
		Digester	High rate pond
1	200.0	27.5	8.3
2	330.0	16.7	5.0
3	413.0	13.0	4.0
4	550.0	10.0	3.0
5	236.0	23.3	7.0

SAMPLING AND ANALYSIS

Raw, anaerobic digester and HRAP effluent samples were collected about one month after the starting of each run to ensure steady-state conditions, and at a frequency of two samples from each source per week. A total of at least ten samples from each source was collected for analysis. The samples were analysed for pH, suspended solids (SS), volatile suspended solids (VSS), total nitrogen (TN), ammonium nitrogen (AN), biochemical oxygen demand of three days' incubation at 30°C (BOD_3), chemical oxygen demand (COD), phosphorus (P) and total alkalinity (Alk). For the raw and anaerobic digester effluents, the TN, AN, BOD_3, COD, P and Alk analyses were on unfiltered samples, but for the HRAP discharge, these analyses were performed on filtered samples. Filtration of samples and analyses were carried out in accordance with procedures adopted by the Rubber Research Institute of Malaysia[7].

RESULTS

Characteristics of raw, anaerobic digester and HRAP effluents are summarised in *Table 2*. Although the pH of the raw effluent was low (4.1 - 5.9), the pH of the anaerobic digester effluent was near neutral, mainly because ammonium nitrogen produced from break-down of organics in the digester contributed to the bicarbonate alkalinity of the effluent[8]. The ammonium bicarbonate alkalinity produced was sufficient to neutralise volatile fatty acids produced from break-down of organics, thus avoiding additional alkalinity. The pH of the HRAP effluent was in the alkaline range due to the removal of dissolved carbon dioxide by the photosynthetic algae[9]. BOD was substantially removed (90% - 96%) in the anaerobic digester, resulting in lower organic carbon to nitrogen ratio of the HRAP influent. Low organic carbon to nitrogen ratios favour growth of photosynthetic organisms[4]. Ammonium nitrogen level in the digester effluent was higher than that of the raw effluent due to mineralisation of organic nitrogen. Phosphorus (greater than 30 mg/litre) was not limiting the growth of algae in the HRAP.

Concentrations of VSS, TN and AN increased with a decrease in the HRAP hydraulic retention time but that of BOD_3 remained low even at the lowest retention time *(Figure 2)*. The HRAP effluent complied with the regulatory standard for BOD_3 even at the lowest retention time. Retention time of at least six days is required to satisfy regulatory standards for nitrogen *(Table 3)*. However, the HRAP effluent still contained a high concentration of suspended solids, mainly due to algae, exceeding the standard for the parameter *(Table 3)*.

DESIGN MODELS

Plug flow and completely-mixed models[11] were examined to select the appropriate design model for the present system comprising of an anaerobic digester and a HRAP operated in series. More complex models were not examined due to lack of data to verify such models. The plug-flow model, considering first-order removal rate, can be expressed as

$$\ln (S_e/S_o) = -kt \qquad \ldots 1$$

where S_o, S_e = influent and effluent limiting substrate concentrations, mg/litre; k = first-order substrate removal rate coefficient, day^{-1}; and t = hydraulic retention time, days. The completely-mixed model, also considering first-order substrate removal rate, can be expressed as

$$S_o/S_e - 1 = kt \qquad \ldots 2$$

BOD_3 indicating biodegradable organic carbon was considered as the limiting substrate for anaerobic digestion and total nitrogen as the limiting substrate for algal growth. That is, other substrates were considered in excess of the respective biosynthetic requirements.

Linear regression analysis with an intercept of zero was used to evaluate the design models using the experimental data in *Table 2*. The results of the statistical analysis are presented in *Table 4*. The coefficient R^2 (the square of correlation coefficient) in *Table 4* is the fraction of the variation in the data explained by the regression model. The completely-mixed model,

TABLE 2. SUMMARY OF EXPERIMENTAL DATA FOR THE ANAEROBIC DIGESTER/HIGH RATE ALGAL POND PILOT-PLANT STUDY

Run	Sample	pH		SS		VSS		COD		BOD_3		TN		AN		P		Alk	
		Mean	cv	Mean	cv	Mean	cv	Mean	cv	Mean	cv	Mean	cv	Mean	cv	Mean	cv	Mean	cv
1	A	5.1	19.2	171	52.0	162	51.8	2 796	14.5	1 977	20.7	164	16.9	64	31.5	45	49.0	289	15.0
	B	7.3	6.6	121	44.6	116	37.6	207	41.1	63	82.0	145	10.9	98	37.5	36	36.2	558	30.0
	C	7.7	4.2	176	39.8	160	50.6	124	34.4	12	51.0	39	34.0	14	32.9	30	9.7	168	22.7
2	A	4.5	13.8	172	46.0	140	60.9	3 171	9.2	2 158	14.6	194	18.1	51	18.7	51	26.4	115	34.0
	B	7.5	8.1	132	32.7	98	56.9	294	29.2	176	36.9	158	2.8	123	7.6	48	13.8	679	3.8
	C	7.8	4.7	222	45.0	192	44.7	125	44.3	23	46.8	54	32.4	41	37.4	38	19.7	289	21.9
3	A	4.1	8.4	452	51.7	402	55.9	3 614	16.3	2 150	13.9	193	20.8	62	14.3	47	3.4	160	63.0
	B	7.1	4.8	143	40.7	124	43.9	514	26.6	257	25.9	146	5.7	104	9.4	44	3.9	655	7.1
	C	7.5	3.0	239	47.6	202	41.1	138	27.8	34	32.0	63	20.3	43	25.6	34	4.2	370	17.4
4	A	5.8	9.7	207	56.3	245	76.8	3 268	42.0	2 572	67.1	295	51.9	140	62.3	86	55.5	595	62.7
	B	6.9	3.3	139	35.5	118	43.3	661	28.1	244	61.6	215	15.7	182	19.5	68	9.7	1044	26.6
	C	7.4	4.2	304	47.7	222	46.6	102	32.0	18	62.6	128	10.2	111	13.0	35	2.9	672	37.7
5	A	5.9	9.6	464	115.0	330	121.0	3 069	19.6	1 490	39.3	173	31.9	56	52.5	53	31.1	—	—
	B	7.7	3.7	107	37.1	83	49.7	205	40.5	60	51.9	146	15.2	107	21.8	52	15.2	—	—
	C	7.6	5.7	179	43.9	153	48.3	92	58.9	14	81.3	42	42.0	23	79.5	49	23.3	—	—

All parameters except pH are expressed in mg/litre

cv = Coefficient of variation (standard deviation/mean), percent
Sample A = Raw effluent
Sample B = Anaerobic digester effluent
Sample C = High rate algal pond discharge

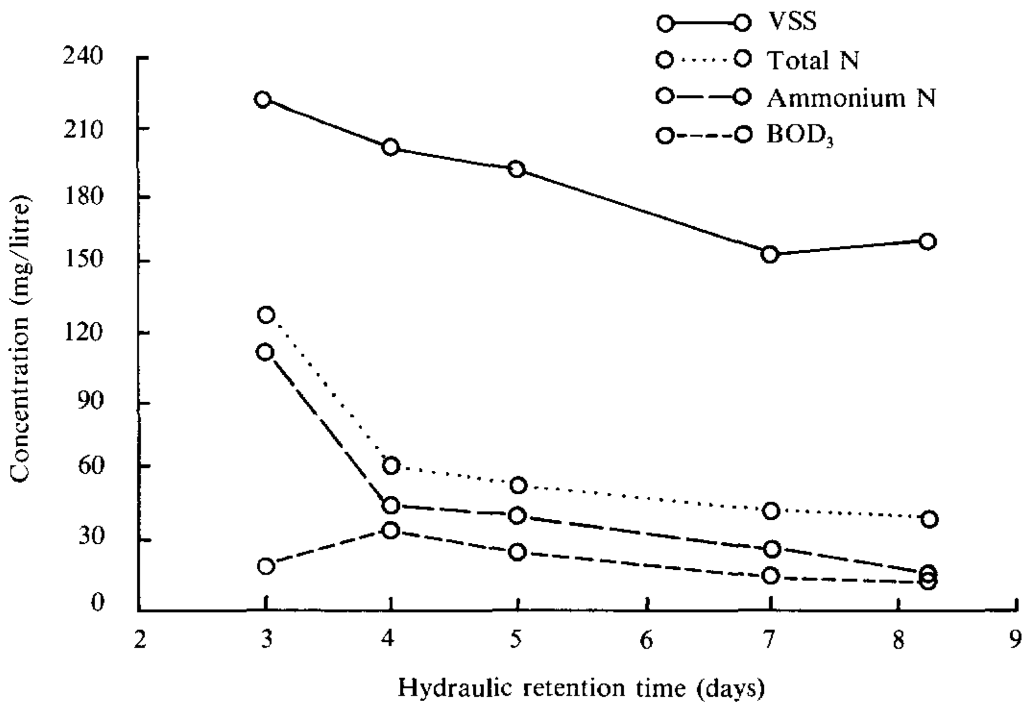


Figure 2. Effect of HRAP hydraulic retention time on the concentrations of VSS, total-N, ammonium-N and BOD_3 of the HRAP effluent.

TABLE 3. STANDARDS FOR WATER COURSE DISCHARGE OF STANDARD MALAYSIAN RUBBER AND CONVENTIONAL GRADE FACTORY

Parameter	Standard
BOD (3 days at 30°C) (mg/litre)	50 (100)[a]
Suspended solids (mg/litre)	100 (150)[a]
Total N (mg/litre)	60[b]
Ammonium N (mg/litre)	40[b]

Source: Department of Environment[10]

[a]No single value to exceed the limit within brackets

[b]On filtered samples

with higher R^2 values in all cases, is statistically the better model to use in designing the anaerobic digester and the HRAP.

DISCUSSION

Values of substrate removal rate coefficients for rubber effluent treatment systems in the literature are scarce. Ahmad *et al.*[12] reported a plug-flow first-order BOD_3 removal rate coefficient value of 0.061 day^{-1} for a full-scale facultative pond treating latex concentrate effluent. This value was lower than the corresponding value for anaerobic pond treating block rubber effluent obtained in the present study *(Table 4)* which could partly be attributed to the presence of high levels of ammonium nitrogen and sulphate in the latex concentrate effluent.

John *et al.*[13] reported the performance of a pilot plant consisting of an anaerobic pond and a facultative pond treating block rubber effluent. From their experimental data, first-order BOD_3 removal rate coefficient for the anaerobic pond and first-order TN removal rate coefficient for the facultative pond, assuming completely-mixed systems, were calculated to be 0.72 day^{-1} and 0.038 day^{-1} respectively. The BOD_3 removal rate coefficient for the anaerobic pond was about 75% of that for the

TABLE 4. STATISTICAL EVALUATION OF DESIGN MODELS FOR ANAEROBIC DIGESTER AND HRAP

System	Model	Limiting substrate	First-order removal rate coefficient (day^{-1})	R^2
Anaerobic	Plug-flow	BOD_3	0.142*	0.90
Anaerobic	Complete-mix	BOD_3	0.958*	0.92
HRAP	Plug-flow	TN	0.179*	0.89
HRAP	Complete-mix	TN	0.339*	0.95

*Statistically significant at 1% level
R^2 = Square of correlation coefficient

anaerobic digester used in the present study and the TN removal rate coefficient for the facultative pond was about 11% of that for the HRAP *(Table 4)*. However, these differences could partly be attributed to size difference of the pilot plants; the volume of the anaerobic pond was seven times larger than that of the anaerobic digester and the surface area of the facultative pond was thirteen times larger than that of the HRAP.

The land areal requirement of HRAP for nitrogen removal could be lower than that of a facultative pond. The first-order total nitrogen removal rate coefficient in the completely-mixed HRAP was found to be 0.339 day^{-1} and that of a 1.2 m deep facultative pond, calculated from experimental data obtained by John *et al.*[13], to be only 0.038 day^{-1}. Considering the rate coefficient and pond depth of the two systems, it was estimated that the use of the 0.35 m deep HRAP could reduce the land area for ponding by about 60%. However, this result could also be influenced by the size difference of pilot plants used, as noted earlier.

An important consideration with HRAP is the possibility of harvesting protein-rich algal biomass. The types of algae developing in the HRAP influence the effectiveness of algal recovery techniques. In the HRAP used, *Chlorella* was observed to be predominating. *Chlorella* spp. are extremely difficult to recover due to their small size (usually less than 20 μm) and negative charge. The small size and negative charge hamper normal separation techniques such as filtration, sedimentation and micro-straining[14]. Economic considerations will not favour the use of energy-intensive methods[15] such as centrifugation and air flotation. Investigation on developing a cost-effective algal recovery system is underway.

CONCLUSIONS

A pilot-plant evaluation of the high rate algal ponding system treating anaerobically digested rubber effluent indicated that the hydraulic retention time of six days is adequate to treat the effluent to satisfy the effluent standards for BOD_3 and nitrogen, but not for suspended solids.

A model based on completely-mixed flow regime was found to be statistically better than that based on plug-flow for the design of the anaerobic digester and the high rate algal pond. Considering the completely-mixed model, the first-order BOD_3 removal rate coefficient in the anaerobic digester was found to be 0.958 day^{-1} and the first order total nitrogen removal rate coefficient in the HRAP was found to be 0.339 day^{-1}.

For nitrogen removal, the land area for a 0.35 m deep HRAP was, based on the pilot plant studies, estimated to be 60% smaller than that of a 1.2 m deep facultative pond.

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