Chapter 3

Results and Discussion

Some results of this research are published as shown in the manuscripts (Appendix A) and not repeated in this Chapter.

3.1 Properties of palm shells

BET Surface area of palm shell is 0.338 sq.m/g while the adsorption BJH pore size distribution is as in *Table 3.1*.

Table 3.1 The adsorption BJH pore size distribution

Pore dia. Range (nm)	Pore volume (ml/g)	%
Under 6	0.00055	20.01
6-8	0.00026	9.67
8-10	0.00015	5.34
10-12	0.00016	5.81
12-16	0.00017	6.12
16-20	0.00017	6.16
20-80	0.00080	29.34
Over 80	0.00048	17.54
BJH Total	0.00274	100.00

3.2 Inlet load and Elimination capacity

In order to prevent the onset of unfavorable conditions, the optimum inlet load must be known. When the inlet loads of VOCs were between 100-250 $g/m^3/h$ the removal efficiencies were mostly 100% (except toluene in mixed system) as can be seen in Figures 3.1 to 3.4. For methanol removal, the maximum elimination capacity was 711 $g/m^3/h$ when the inlet loads were 50-1120 $g/m^3/h$. When the inlet loads were 33-648 $g/m^3/h$ the maximum elimination capacity of toluene system was 346 $g/m^3/h$. In mixed system, the maximum elimination capacities of methanol and toluene were 703 and 222 $g/m^3/h$, respectively.

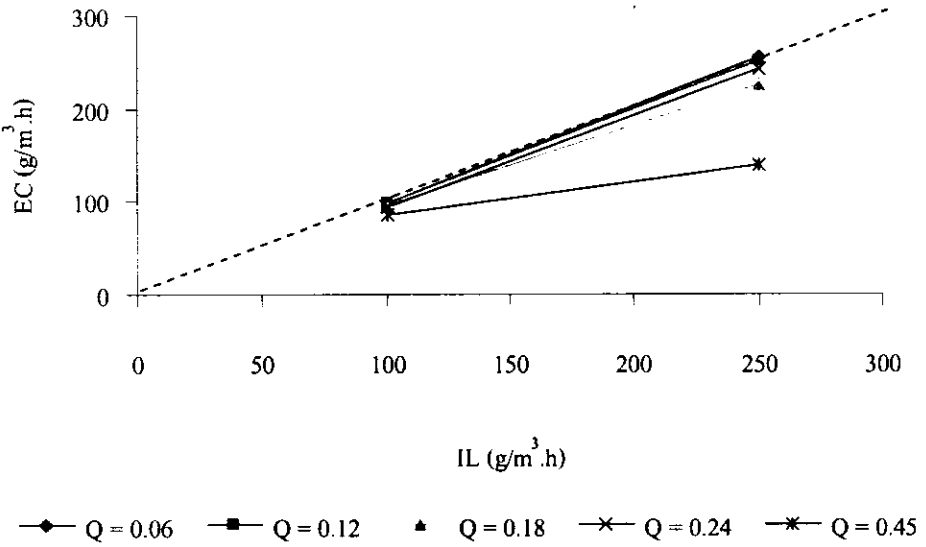

Figure 3.1 Inlet load and elimination capacity of methanol at various flow rates.

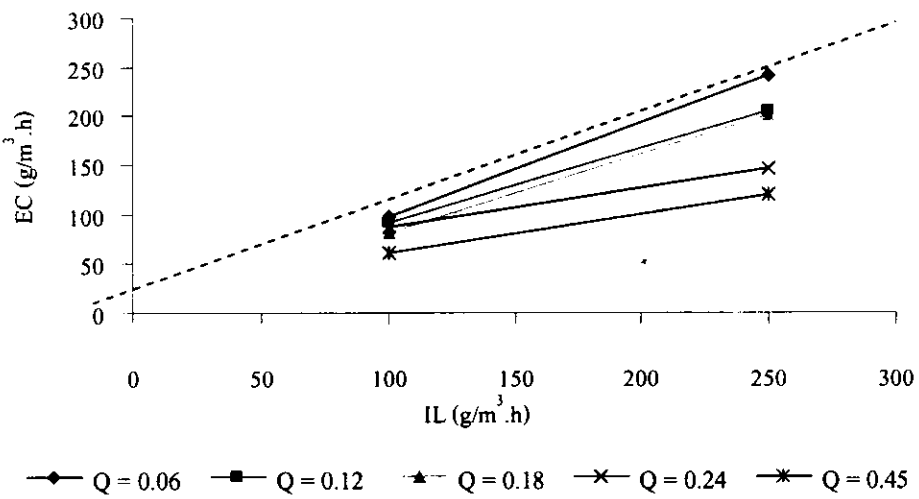

Figure 3.2 Inlet load and elimination capacity of toluene at various flow rates.

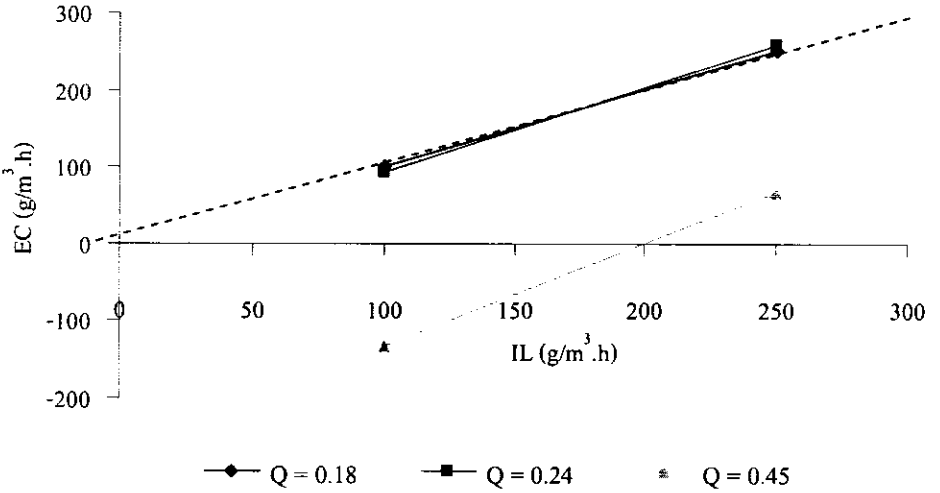

Figure 3.3 Inlet load and elimination capacity of methanol in mixed system at various flow rates.

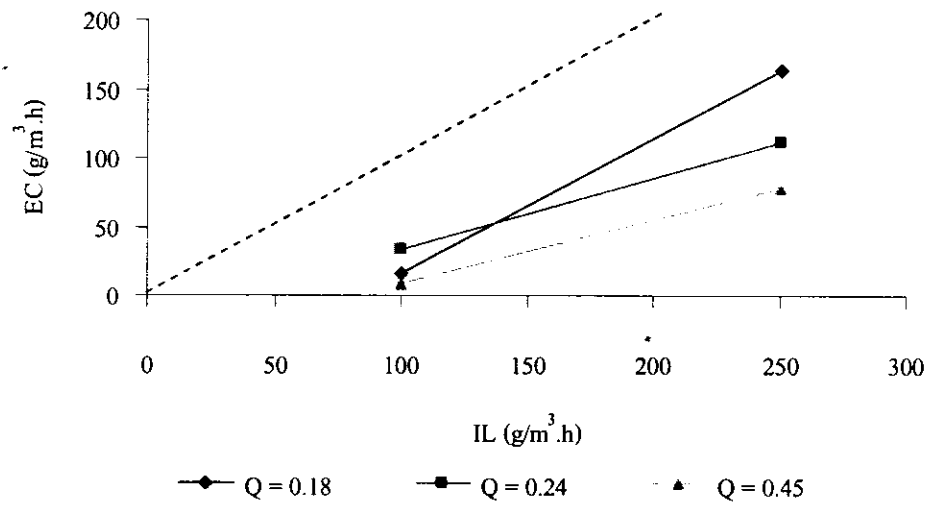

Figure 3.4 Inlet load and elimination capacity of toluene in mixed system at various flow rates.

The removal rates obtained in this study were comparable to (or higher than) the results obtained by other researchers working on the removal of VOCs using biofilter with different media compositions as shown in Table 3.1.

Table 3.1 Performance comparison between this work and other biofiltration studies.

Study	Type of VOC	Media	IL max ($g/m^3/h$)	EC max ($g/m^3/h$)
Mohseni and Allen	Methanol	Compost + wood chips	280	250
Zilli *et al.*	Toluene	Specific microorganisms	1100	242
Delhomenie *et al.*	Toluene	Compost	65	55
Yoon and Park	Toluene	Peat	4855	3977
Torkian *et al.*	Toluene	Compost+wood chips	105	78
This study	Methanol	Activated sludge + Palm shells	1120	711
	Toluene	Activated sludge + Palm shells	648	346
	Methanol[a]	Activated sludge + Palm shells	703	703
	Toluene[a]	Activated sludge + Palm shells	494	222

[a]mixed system between methanol and toluene.

This suggests that a mixture of palm shells and activated sludge can be used as the filter bed media for an efficient biofilter.

3.3 Removal efficiency

The removal efficiency varied with flow rate or EBRT. During concentration of 0.3 to 2.5 g/m^3, VOCs were removed almost 100% at flow rate of 0.06-0.24 m^3/h for methanol and 0.06-0.18 m^3/h for toluene. However, they were not successively treated at flow rate of 0.45 m^3/h because VOCs did not have enough time to contact, attach, diffuse, and biodegrade with microorganisms.

Figure 3.5, along with Table 3.2, shows that during stages B to G, the removal efficiencies of methanol were mostly maintained at 100%. The biofilter provided methanol removal as high as 750 g methanol/m^3 bed medium/h at retention times as low as 9 s and in some instances up to 1120 g/m^3h at retention time of 12 s. Figure 3.6, along with Table 3.3, shows that during stages B and C the removal efficiencies of toluene were nearly maintained at 100%. The biofilter provided toluene removal as high as 298 g/m^3h at retention times as low as 24 s and in some instances up to 647 $g/m^3/h$ at retention time of 9 s.

For removal of methanol in mixed system, the removal efficiencies of methanol were almost maintained at 100% during stages D and E, so stages B and C also 100%. The biofilter provided methanol removal as high as 707 $g/m^3/h$ at retention times as low as 12 s and in some instances up to 583 $g/m^3/h$ at retention time of 9 s (Figure 3.7 and Table 3.4). The biofilter provided toluene removal in mixed system as high as 528 g/m^3h at retention times as low as 12 s and in some instances up to 494 $g/m^3/h$ at retention time of 9 s (Figure 3.8 and Table 3.5). Even if concentration of toluene in mixed system was 0.7 g/m^3, which was less than pure toluene system, toluene in mixed

system did not tend to steady state. This data can discuss that microorganisms using methanol for growth had effected to microorganisms using toluene for growth that crossed link was occurred between both microorganisms.

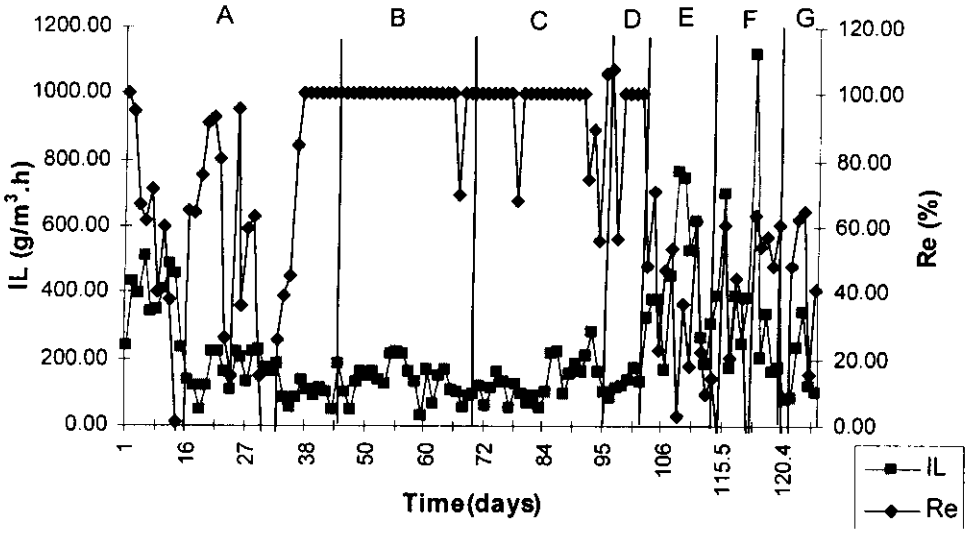

Figure 3.5 Inlet load concentration of methanol and removal efficiency as a function of time (IL: Inlet load, RE: Removal efficiency).

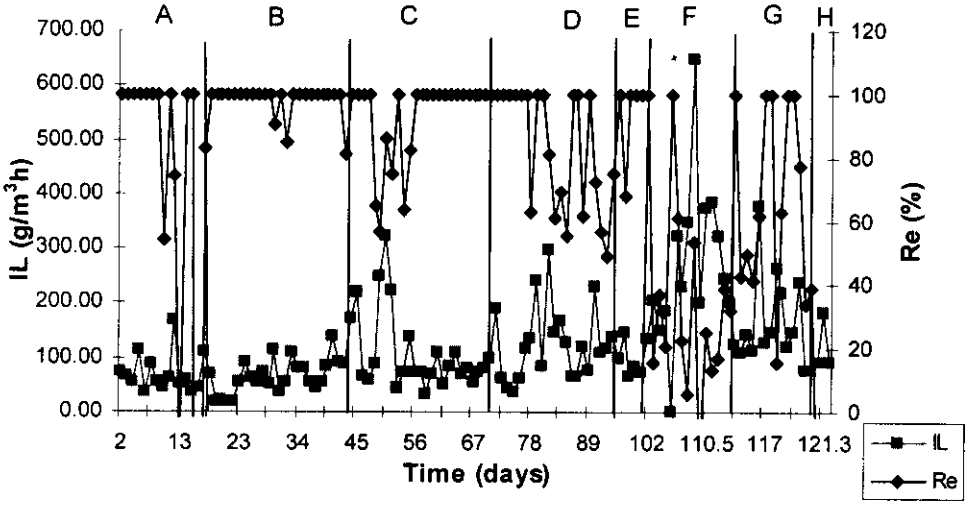

Figure 3.6 Inlet load concentration of toluene and removal efficiency as a function of time (IL: Inlet load, RE: Removal efficiency).

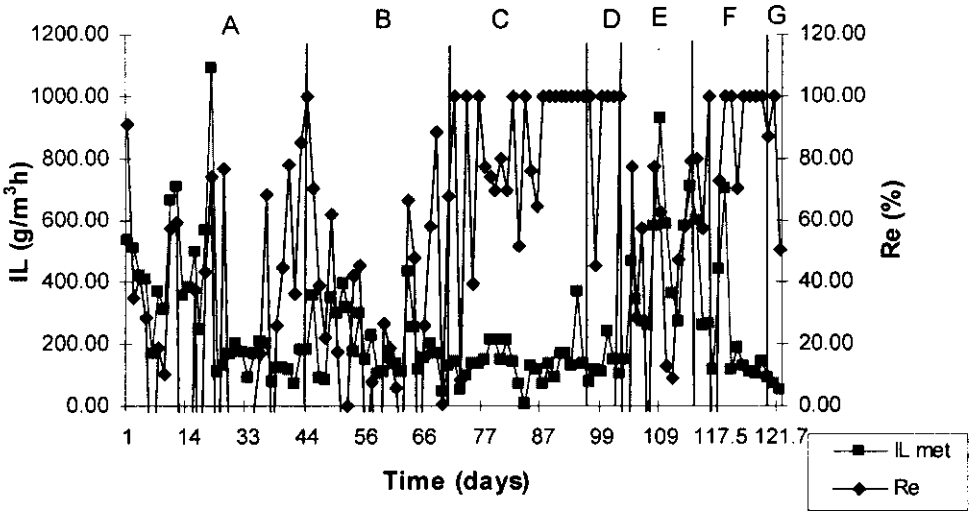

Figure 3.7 Inlet load concentration of methanol mixed system and removal efficiency as a function of time (IL: Inlet load, RE: Removal efficiency).

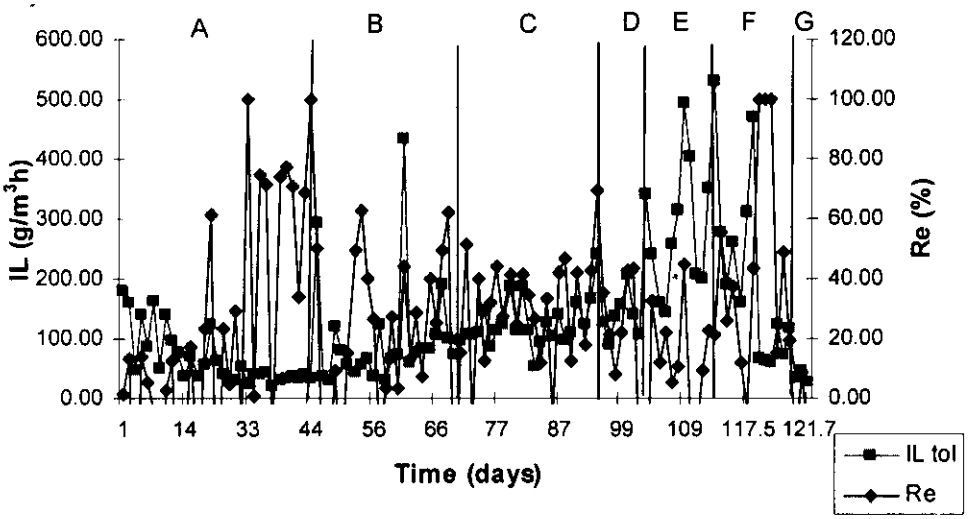

Figure 3.8 Inlet load concentration of toluene in mixed system and removal efficiency as a function of time (IL: Inlet load, RE: Removal efficiency).

Table 3.2 Experimental data for biofiltration of methanol at room temperature.

Day	Inlet conc. (g/m^3)	Flow rate (m^3/h)	EBRT (S)	Outlet conc. (g/m^3)	RE (%)	IL ($g/m^3/h$)	EC ($g/m^3/h$)
37	2.7	0.06	71	0	100	135.6	135.6
41	2.3	0.06	71	0	100	116.7	116.7
42	1	0.06	71	0	100	49.5	49.5
44	1.8	0.12	35	0	100	188.1	188.1
47	0.5	0.12	35	0	100	134.0	134.0
50	1.4	0.12	35	0	100	147.0	147.0
55	2.2	0.12	35	0	100	224.3	224.3
61	0.7	0.12	35	0	100	66.3	66.3
70	0.6	0.18	24	0	100	95.6	95.6
72	0.4	0.18	24	0	100	60.5	60.5
74	1	0.18	24	0	100	159.2	159.2
86	1.4	0.18	24	0	100	221.4	221.4
93	1.8	0.18	24	0.2	89.13	280.4	249.9
99	0.6	0.24	18	0	100	120.9	120.9
100	0.7	0.24	18	0	100	138.6	138.6
102	0.4	0.45	9	0	100	133.6	133.6
103	0.8	0.45	9	0.4	47.8	323.0	154.5
106	0.5	0.45	9	0.2	47.0	170.7	80.2
107	1.2	0.45	9	0.6	53.4	452.4	241.6
110	2.0	0.45	9	1.2	36.8	750.4	276.1
113	0.7	0.45	9	0.7	9.6	183.2	26.4
116	0.7	0.3	12	0.5	20.5	171.2	35.2
118	4.4	0.3	12	1.6	63.5	1119.9	711.2
120	0.9	0.3	12	0.5	47.9	159.9	76.5

Table 3.3 Experimental data for biofiltration of toluene at room temperature.

Day	Inlet conc. (g/m^3)	Flow rate (m^3/h)	EBRT (S)	Outlet conc. (g/m^3)	RE (%)	IL ($g/m^3/h$)	EC ($g/m^3/h$)
18	1.4	0.06	71	0	100	70.1	70.1
19	0.3	0.06	71	0	100	17.2	17.2
23	1.1	0.06	71	0	100	56.8	56.8
24	1.8	0.06	71	0	100	90.6	90.6
32	2.1	0.06	71	0	100	108.4	108.4
40	2.7	0.06	71	0	100	138.7	138.7
44	1.7	0.12	35	0	100	172.3	172.3
45	2.2	0.12	35	0	100	219.4	219.4
50	2.5	0.12	35	1.07	56.5	250.7	141.6
56	0.7	0.12	35	0	100	75.0	75.0
58	0.3	0.12	35	0	100	33.4	33.4
60	.1	0.18	35	0	100	110.0	110.0
82	1.9	0.18	24	0.37	80.8	296.7	239.8
84	1.1	0.18	24	0.34	69.1	169.4	117.1
85	0.8	0.18	24	0.37	55.2	127.9	70.6
87	0.4	0.24	24	0	100	64.9	64.9
96	0.5	0.24	18	0	100	98.2	98.2
98	0.7	0.45	18	0.23	68.1	147.6	100.4
102	0.4	0.45	9	0	100	137.4	137.4
105	0.5	0.45	9	0.39	20.7	187.4	38.9
107	0.9	0.45	9	0.33	60.7	323.1	196.0
110	1.7	0.45	9	0.8	53.5	647.7	346.2
111	1.0	0.45	9	0.7	25.1	374.8	94.0
113	0.6	0.45	9	0.4	39.2	244.0	95.7
115	0.4	0.3	12	0.2	42.95	111.5	47.9
117	1.5	0.3	12	0.6	61.6	375.8	231.5
117.5	0.5	0.3	12	0.0	100.0	127.0	127.0
119	1.0	0.3	12	0.9	15.94	264.2	42.1
120	0.5	0.3	12	0.0	100	120.3	120.34

Table 3.4 Experimental data for biofiltration of methanol in mixed system at room temperature.

Day	Inlet conc. (g/m^3)	Flow rate (m^3/h)	EBRT (S)	Outlet conc. (g/m^3)	RE (%)	IL ($g/m^3/h$)	EC ($g/m^3/h$)
87	0.5	0.18	24	0	100	72.2	72.2
88	0.9	0.18	24	0	100	132.7	132.7
91	1.1	0.18	24	0	100	167.4	167.4
94	2.4	0.18	24	0	100	366.5	366.5
96	0.4	0.24	18	0	100	74.2	74.2
99	0.5	0.24	18	0	100	110.5	110.5
100	1.2	0.24	18	0	100	235.9	235.9
101	0.7	0.24	18	0	100	148.1	148.1
102	0.3	0.45	9	0	100	105.8	105.8
104	1.2	0.45	9	0.3	77.4	464.2	359.5
106	0.7	0.45	9	0.3	57.7	269.4	155.4
108	1.5	0.45	9	0.4	77.3	582.5	449.9
109	2.4	0.45	9	0.9	62.8	926.2	582.0
113	1.5	0.45	9	0.6	58	580.3	336.5
114	2.8	0.3	12	2.8	79.4	707.7	561.6
116	1.0	0.3	12	1.0	100.0	262.8	262.8
118	2.8	0.3	12	2.8	100.0	703.2	703.2
120	0.8	0.3	12	0.8	100.0	131.0	131.0

Table3.5 Experimental data for biofiltration of toluene in mixed system at room temperature.

Day	Inlet conc. (g/m^3)	Flow rate (m^3/h)	EBRT (S)	Outlet conc. (g/m^3)	RE (%)	IL ($g/m^3/h$)	EC ($g/m^3/h$)
87	0.9	0.18	24	0.5	41.9	138.8	58.1
88	0.6	0.18	24	0.3	46.7	96.1	44.9
91	1.0	0.18	24	0.6	41.9	159.4	66.8
94	1.6	0.18	24	0.5	69.5	239.9	166.8
96	0.4	0.24	18	0.3	21.4	90.5	19.4
99	0.8	0.24	18	0.6	21.8	156.4	34.1
100	1.0	0.24	18	0.6	42.7	206.7	88.2
101	0.7	0.24	18	0.4	43.3	138.3	56.0
102	0.3	0.45	9	0.4	-25.7	108.1	-28.0
104	0.6	0.45	9	0.4	32.9	240.3	79.0
106	0.4	0.45	9	0.3	21.9	141.8	31.0
108	0.8	0.45	9	0.7	10.4	313.9	32.6
109	1.3	0.45	9	0.7	45.0	494.0	222.2
113	0.9	0.45	9	0.7	22.9	350.6	80.4
114	2.1	0.3	12	1.6	21.1	528.9	111.4
116	1.0	0.3	12	0.6	37.1	259.6	96.4
118	1.9	0.3	12	1.1	43.3	470.1	203.8
120	0.2	0.3	12	0	100	62.2	62.2

The removal efficiencies obtained in this study were comparable to (or higher than) the results obtained by other researchers working on the removal of VOCs using biofilter with different diameter and height as shown in Table 3.6.

Table 3.6 Performance comparison between this work and other biofiltration studies.

Study	Type of VOC	Diameter and Height (cm)	EBRT (s)	RE_{max} (%)
Mohseni and Allen	Methanol	28, 120	30	98
Zilli *et al.*	Toluene	5, 65	101	100
Delhomenie *et al.*	Toluene	15.3, 135.3	65	95
Yoon and Park	Toluene	5, 62	90	94
Torkian *et al.*	Toluene	8, 150	60	94
This study	Methanol	5, 98	71-18	100
	Toluene	5, 98	71-24	100
	Methanol[a]	5, 98	71-18	100
	Toluene[a]	5, 98	9	30

[a]mixed system between methanol and toluene

3.4 Optimal conditions

From our experiments, the optimum conditions for biofiltration systems can be decided as shown in Table 3.7 and 3.8.

Table 3.7 The optimum flow rate at different concentration range.

Concentration (g/m^3)	Flow rate in pure toluene system (m^3/h)	Flow rate in pure methanol system (m^3/h)	Flow rate of methanol in mixed system (m^3/h)
<0.5	0.06-0.24	0.06-0.24	0.06-0.24
0.5-1	0.06-0.12	0.06-0.24	0.06-0.24
1-1.5	0.06-0.12	0.06-0.18	0.06-0.24
1.5-2.5	0.06	0.06-0.12	0.06-0.24

Table 3.8 The optimum flow rate with elimination capacity.

Elimination capacity ($g/m^3/h$)	Flow rate in pure toluene system (m^3/h)	Flow rate in pure methanol system (m^3/h)	Flow rate of methanol in mixed system (m^3/h)
<100	0.06-0.24	0.06-0.24	0.06-0.24
100-250	0.06-0.18	0.06-0.24	0.06-0.24
>250	0.06-0.18	0.06-0.24	0.06-0.24

3.5 Nitrogen test

Reduction of VOCs might come from two phenomena: adsorption and biodegradation. Stage H was investigated whether the system was dominated by microorganisms biodegradation or adsorption. This stage was operated by nitrogen test method at days 121-122. Nitrogen was added instead of air in the system. So, the microorganisms should not degrade VOCs because the lack of oxygen. Figure 3.9 shows the inlet concentration and outlet concentrations of methanol at different column heights. It was observed that at the beginning the outlet concentrations of methanol were lower than the inlet concentration. This might be because there was some oxygen left in the biofiltration system. In addition, from study of adsorption of dry palm shells in biofilter column the media was saturated by VOCs in 5 days. Therefore, the reduction of VOC after that time should be dominated by biodegradation process rather than adsorption process. This idea is supported by the result that the outlet concentrations of methanol were nearly equal to the inlet concentration of methanol after one day of nitrogen test. Similar results were observed in the case of removal of toluene and mixed system as shown in Figures 3.10 and 3.11, respectively.

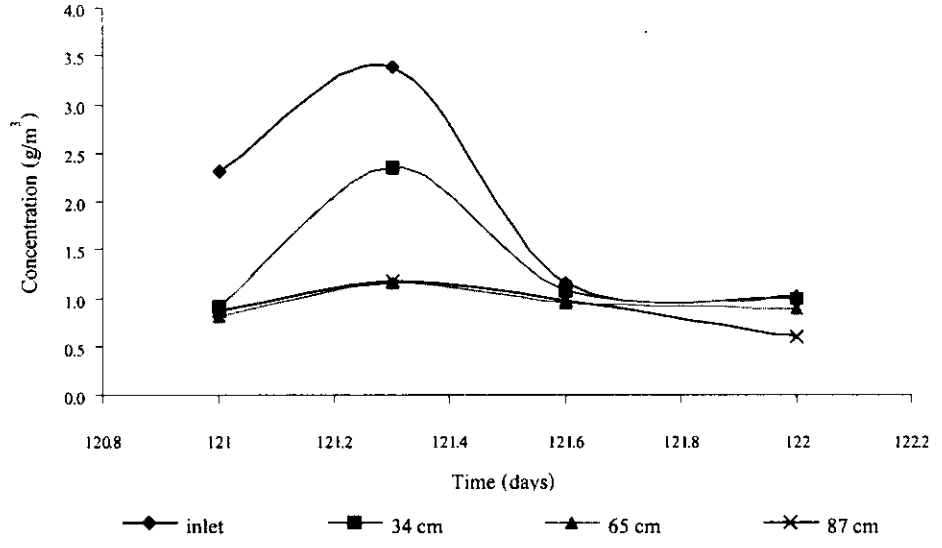

Figure 3.9 Nitrogen test: influence of the concentration of methanol and times of the biofilter at different heights at constant flow rate of 0.2 m^3/h.

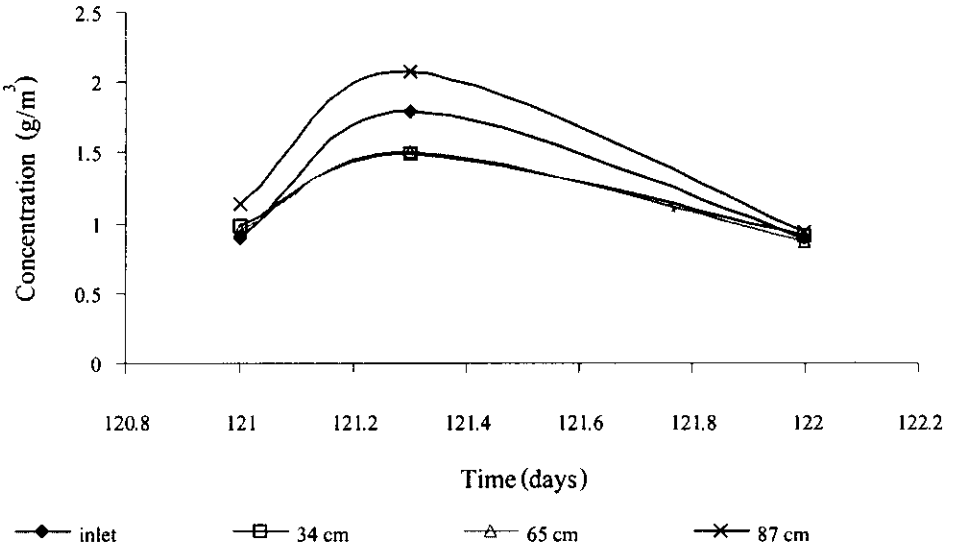

Figure 3.10 Nitrogen test: influence of the concentration of toluene and times of the biofilter at different heights at constant nitrogen flow rate of 0.2 m^3/h.

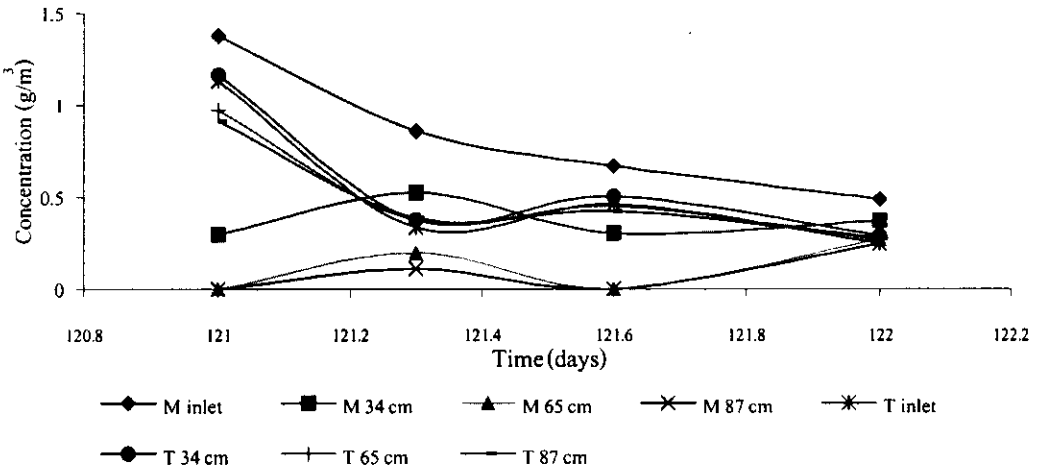

Figure 3.11 Nitrogen test: influence of the concentration of mixed VOCs and times of the biofilter at different heights at constant nitrogen flow rate of 0.2 m^3/h, M = Methanol and T = Toluene.