H_2S and VOC Removal at Headworks
Hyperion Treatment Plant

Draft Interim Report II

July 2001

**Applied Research (WESD), Hyperion Treat. Plant
and EMD, Bureau of Sanitation, City of LA**

**UC Riverside, Riverside, CA
UC Davis, Davis, CA
Water Environment Research Foundation**

CITY OF LOS ANGELES

INTER-DEPARTMENT CORRESPONDENCE

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TO: Distribution

FROM: Omar Moghaddam, Energy Management & Applied Research/WESD

SUBJECT: **H2S and VOCs Removal at Headworks, Hyperion Treatment Plant**
Interim Report II

This is the Second Interim Report by Applied Research Group/WESD on the progress of the subject matter. Interim Report I discussed information on biofilter and biotrickling filter technologies with focus on the H2S removal efficiencies.

This report covers the effect of removal efficiency for volatile organic compounds (VOCs) in three phases.

We are now in the process of project close-out and completing a cost study on applications of these technologies for our wastewater treatment facilities.

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EXECUTIVE SUMMARY

BACKGROUND

Based on the recommendations for future studies outlined in our Interim Report I (distribution on December, 2000), the staff from the Applied Research Group (ARG) in collaboration with UC Riverside and UC Davis conducted additional testing with biofilter (BF) and biotrickling filter (BTF). These tests cover the effect of removal efficiency (RE) for high volatile organic compounds (VOCs) in three phases:

Phase I: Gasoline injection, October 2000
  a. With pH =1-2 at BTF(week of 16-20, October)
  b. With pH = 7-8 at BTF (week of 24-31, October).
Phase II: Gasoline and Mixture (methylene chloride and trichloroethylene (TCE)) injection, November 2000
Phase III: No injection, December 2000

All other parameters such as, moisture content, nutrient rate for BTF, sprinkling rate for BF, high-pressure effluent (HPE) feed rate for BTF, gas flow rate for both BF and BTF, and both filter media remains unchanged in all the experiments. The injection rate of gasoline was 50 μl/second and the injection rate of mixture of methylene chloride and TCE was 25 μl/second. Immediately after the injection, the concentration of non-halogenated VOCs was increased.

The inlet concentration of benzene, toluene, total xylenes, dichloromethane, chloroform, trichloroethylene, tetrachloroethylene, and dichlorobenzenes were beyond method detection limit (MDL).

The overall results indicate that despite the large increase in VOCs loading BF performance remains similar to removal of VOCs concentrations in natural flows at headworks. This shows any upset or shock in influent concentration of VOCs at HTP plant does not have any major effect on VOCs removal for BF. BTF VOCs removal efficiency stayed low as in previous experiment and in some cases the removal become worse.

Biofilter / VOCs removal

VOCs removal efficiencies varied greatly, also depending on the experimental conditions. Average values and ranges of removal efficiencies as well as the range of inlet concentrations during each experimental period are summarized in **Table ES-1.** Throughout the entire experiment fairly good removal of non-chlorinated VOCs (benzene, toluene and xylenes) were observed with removal efficiencies between 20-100%.

Removal efficiencies of non-chlorinated VOCs were about the same when increasing the concentration during spiking experiments. The removal of chlorinated VOCs were initially poor (day 29-59). However, spiking with toluene or gasoline seemed to improve biodegradation of these compounds. One possible explanation could be that extra supply non-chlorinated VOCs stimulates the growth of a multi-species heterotrophic population, which is also capable of removing chlorinated VOCs.

Spiking with chlorinated VOCs (dichloromethane and trichloroethylene) had an adverse effect on the biodegradation of the spiked compounds, as well as on other VOCs in general. This strongly suggests a toxic effect of dichloromethane and trichloroethylene at elevated concentrations in the biofilter.

Biotrickling filter / VOCs removal

Average VOCs removal data are presented in **Table ES-2**, which were calculated from individual measurements. In some cases VOCS concentrations were higher at the outlet than at the inlet (negative removal efficiency). This is believed to be due to a combination of fluctuating VOCS concentrations in the headworks' air, a 5-10 min delay in sampling between the inlet and outlet, and possibly absorption/desorption effects. Throughout the entire experimental period of 280 days, removal of VOCs were poor, irrespective of experimental conditions. No removal of xylenes and any of the chlorinated hydrocarbons were observed. Moderate but significant removal of toluene and benzene occurred when a neutral pH in biotrickling filter was maintained (days 46-133). This emphasizes that pH control is required for VOCs removal, but other factors play a role as well because relatively biodegradable compounds such as xylenes and dichloromethane were not removed at a neutral pH.

The objective of the VOCs spiking experiment was to stimulate VOCs removal, either by enhancing the growth of VOCs-degrading microorganisms or by induction of specific enzymes. The concentrations of benzene, toluene, xylenes, dichloromethane and trichloroethylene were increased by two to three orders of magnitude, but no improvement of removal was observed (**Table ES-2**). VOCs removal requires the presence of microorganisms capable of VOCs biodegradation, as well as environmental conditions that stimulate their activity. At this point it is not clear why the spiking experiment failed in enhancing VOCs removal. Toxicity of the VOCs during the spiking experiments can be ruled out as the literature has presented examples of biodegradation in biotrickling filters at much higher concentrations.

Table ES-1. VOCs removal in the biofilter: average removal efficiencies (RE) and range of inlet concentrations during five experimental periods.

Pollutant	Day 29-59		Day 133-136		Day 196-204		Day 217-226		Day 240-241	
	Standard operation		Toluene spiking[b]		Gasoline spiking		Gasoline & chlorinated VOCS spiking		Standard operation	
	RE (%)[a]	Inlet range (ppb)	RE (%)	Inlet range (ppb)	RE (%)	Inlet range (ppb)	RE (%)	Inlet range (ppb)	RE (%)	Inlet range (ppb)
Benzene	74 (34 – 100, 19)	3 – 6	27 (5 – 59, 7)	3-12	**71 (54 – 84, 7)**	**315 – 485**	**17 (5 – 33, 5)**	**185 – 245**	25 (2)	6 – 8
Toluene	79 (43 – 100, 19)	43 –117	**59 (14 – 99, 6)**	**4800-42000**	**71 (49 – 84, 7)**	**1705 – 2450**	**26 (9 – 39, 6)**	**900 – 1310**	70 (2)	35 – 41
Xylenes	56 (8 – 93, 19)	29 – 143	55 (18 – 93, 7)	40-118	**52 (26 – 67, 7)**	**2300 – 3300**	**41 (28 – 53, 6)**	**1115 – 1710**	47 (2)	32
Dichlorobenzenes	19 (-18 – 42, 18)	5 – 22	58 (17 – 100, 7)	2-14	28 (8 – 50, 7)	10 – 21	4 (4, 2)	8 – 9	50 (2)	14 – 19
Dichloromethane	7 (-43 – 65, 19)	12 – 96	59 (-12 – 95, 7)	17 – 49	79 (68 – 87, 7)	24 – 70	**-31 (-17 – 50, 6)**	**4065 – 9880**	17 (13 – 22, 2)	16 – 22
Chloroform	0 (-7 – 11, 19)	38 – 108	6 (-8 – 35, 7)	53-100	3 (-4 – 8, 7)	54 – 86	-2 (-5 – 1, 2)	51 – 73	7 (5 – 10, 2)	72 – 74
Tetrachloroethylene	-1 (-5 – 3, 19)	51 – 130	19 (-11 – 90, 7)	24 – 72	0 (-7 – 6, 7)	43 – 226	-13 (-34 – 8, 3)	75 – 125	7 (5 – 10, 2)	54 – 96
Chlorobenzene	79 (40 – 100 , 8)	0 – 2		0	NA	NA		0		0
Trichloroethylene	0 (-10 – 7, 9)	6 – 11	13 (-8 – 62, 7)	2 – 7	NA	NA	**-49 (-34 – 6, 5)**	**1905 – 4200**	-17 (-31 - -4, 2)	3

[a] In parentheses the range and number of determinations is given

[b] Values in bold represent spiking experiments with increased concentration

Table ES-2. VOCs removal in the biotrickling filter: average removal efficiencies (RE) and range of inlet concentrations during four experimental periods.

Pollutant	Days 14, 28, 30 No pH control, acidic pH		Days 57, 60, 133 PH control, neutral pH		Days 196, 198[b] PH control, acidic pH, spiking experiment[c]		Days 204 to 226 PH control, neutral pH, spiking experiment		Days 240, 241 PH control, neutral pH	
	RE (%)[a]	Inlet range (ppb)	RE (%)	Inlet range (ppb)	RE (%)	Inlet range (ppb)	RE (%)	Inlet range (ppb)	R E (%)	Inlet range (ppb)
Benzene	0 (12)	1-22	35 (7)	8-13	**3 (5)**	**331-483**	**6 (9)**	**183-360**	13 (2)	6-8
Toluene	-4 (12)	10-153	36 (7)	38-73	**3 (5)**	**1700-2470**	**6 (10)**	**900-2310**	9 (2)	35-41
Xylenes	-3 (12)	13-120	-2 (7)	19-124	**4 (5)**	**2300-3300**	**8 (10)**	**1115-2965**	6 (2)	32
Dichlorobenzenes	-19 (12)	1-9	-14 (7)	11-17	-2 (5)	10-21	-1 (6)	8-20	7 (2)	14-19
Dichloromethane	-2 (12)	4-43	-3 (7)	11-63	1 (5)	24-60	**-8 (6)**	**4065-9880**	18 (2)	16-22
Chloroform	-2 (12)	16-76	-4 (7)	58-102	0 (5)	54-86	-1 (6)	51-87	3 (2)	72-74
Tetrachloroethylene	-2 (12)	15-89	4 (7)	33-151	-1 (5)	54-226	-3 (7)	43-157	8 (2)	54-96
Chlorobenzene	(2)	0	25 (4)	1-2	0 (1)	1	14 (2)	1		
Trichloroethylene	-4 (2)	1	-5 (7)	4-15	6 (3)	5-6	**-6 (6)**	**1905-4200**	-8 (2)	3

[a] Value in parentheses represents the number of determinations.

[b] During days 196-198, failure of the pH controller caused an acidic pH in the recycle liquid.

[c] Values in bold represent spiking experiments with increased pollutant concentrati

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ACRONYMS

BF	BIOFILTER
BTF	BIOTRICKLING FILTER
BTEX	BENZENE TOLUENE ETHYL XYLENE
CARB	CALIFORNIA AIR RESOURCE BOARD
EPA	ENVIRONMENT PROTECTION AGENCY
ELCD	ELECTROLYTE CONDUCTIVITY DETECTOR
GC	GAS CHROMATOGRAPHY
HTP	HYPERION TREATMENT PLANT
HP	HORSE POWER
HPE	HIGH PRESSURE EFFLUENT
MDL	METHOD DETECTION LIMIT
MGD	MILLION GALLON PER DAY
PID	PHOTO IONIZATION DETECTION
POTW	PUBLIC OWNED TREATMENT WORK
PVC	POLY VINYL CHLORIDE
PPM	PARTS PER MILLION
PPB	PARTS PER BILLION
SCAQMD	SOUTHERN CALIFORNIA AIR QUALITY MANAGEMENT DISTRICT
UCR	UNIVERSITY OF CALIFORNIA, RIVERSIDE
UCD	UNIVERSITY OF CALIFORNIA, DAVIS
VOCs	VOLATILE ORGANIC COMPOUNDS
WERF	WATER ENVIRONMENT RESEARCH FOUNDATION

1. INTRODUCTION

Based on the recommendation for future studies outlined in our interim Report, the Applied Research Group (ARG) staffs in collaboration with UC Riverside and UC Davis staff conducted several testing in biotrickling filter (BTF) and biofilter (BF). The purpose of these testing was to investigate the effect of high volatile organic compounds (VOCs) concentration in performance of BTF and BF. These testing were performed in three phases:

- Phase I: During the month of October 2000 (gasoline injection)
  - c. With pH =1-2 at BTF(week of 16-20 October)
  - d. With pH = 7-8 at BTF (week of 24-31 October).
- Phase II: During the Month of November 2000 (gasoline and Mixtures; mixture of methylene chloride and trichloroethylene (TCE) injection)
- Phase III: During the month of December 2000 with no injection

All other parameters such as, moisture content, nutrient rate for BTF, sprinkling rate for BF, high-pressure effluent (HPE) feed rate for BTF, gas flow rate for both BF and BTF, both filter media remains unchanged. The injection rate of gasoline was 50 μl/second and the injection rate of mixture of methylene chloride and TCE (Mixtures) was 25 μl/second. Immediately after the injection, the concentration of non-halogenated VOCs was increased. An overview of the set-up and specific experiments with the biotrickling filter and biofilter is presented in **Table 1.**

Table 1. Time course of experiments with the biotrickling filter (BTF) and biofilter (BF)

Day	Reactor	Experiment
0	BTF & BF	Start (4-3-2000) standard operation. No pH control in the BTF.
46	BTF	Start pH control in the BTF.
71	BTF & BF	CO_2 tracer studies.
133-136	BF	Spiking of toluene.
190-227	BTF & BF	Spiking of gasoline (source of benzene, toluene and xylenes).
211-227	BTF & BF	Spiking of dichloromethane and trichloroethylene.
254	BTF & BF	Complete performance analysis: H_2S, organic sulfur compounds, VOCs, and odor.

2. MATERIAL AND METHODS

2.1 Experimental Set Up

Samples were collected by connecting 10 L Tedlar bags to the inlet and outlet air-ducts. Over-pressure in the air-ducts was sufficiently high to fill the bags without other means and 8-9 L of sample air was collected in about 3-4 min. VOCs analysis were done by the Air Laboratory of Environmental Monitoring Division (EMD) according to modified EPA method TO-14 using a GC with photoionization and electrolyte conductivity detection. The method detection limit was 0.5 ppbv for most VOCs and up to 2 ppbv for others. Vinyl chloride, vinylidene chloride, carbon tetrachloride, 1,1-dichloroethane, 1,2-dichloroethane, benzylchloride and methylchloroform were always below the detection limit.

Experiments with the pilot-plant units started on April 3, 2000 (day 0 in graphs), on which day both reactors were inoculated with recycle liquid of H_2S-degrading biotrickling filters. The biotrickling filter also received raw influent water from the plant. The biofilter and biotrickling filter treated the same air from the headworks' building at empty bed gas residence times (EBRT) of 20-50 s and 15-25 s, respectively. The fluctuations observed in the gas flow rates were probably due to slight variations of the pressure in the inlet air, and for the biofilter also to increasing head losses across the packed bed. The biotrickling filter was initially operated without pH control. After 46 days, automatic pH control was initiated to maintain a pH above 7.0.

Long-term performance of the reactors was determined on a (semi)-daily basis with determination of the gas flow rate and the pressure drop and analysis of H_2S inlet and outlet concentrations. For the biotrickling filter, also the recycle liquid pH, the secondary effluent feed rate, the purge rate and caustic soda consumption were recorded. VOCS removal was determined on selected days over the entire experiment.

Concentrations of selected VOCs were temporarily increased in spiking experiments with the objective to stimulate their removal. This was done by continuous feed of the (liquid) VOCs into the main air stream to the biofilter and biotrickling filter using a Master flex pump

3. RESULTS AND DISCUSSION

3.1 Long term hydrogen sulfide removal (October –December 2000)

With the addition of gasoline and mixtures the removal efficiency of hydrogen sulfide did not change for both BF and BTF. The same trends were observed for hydrogen sulfide as reported in Interim Report I. The removal efficiencies for both systems were in range of 99 to 100 percent. Two graphs of long term performance of hydrogen sulfide for both BF and BTF are shown in Figures 1 and 2.

3.2 VOCs Results

3.2.1 Phase I: Volatile Organic Compounds (VOCs) Removal (October 2000)

3.2.1.1 Biofilter

3.2.1.1.1 Nonhalogenated VOCs

With the addition of gasoline, no major changes were observed for removal of non-halogenated VOCs for BF. The average removal efficiencies for benzene, toluene and total xylenes (BTX) were 68, 66.7 and 44 respectively. . However, during the second week (10/24- 10/30), a small decrease was observed in BTX removal. These trends are shown for BTX graphs for biofilter. This is a good indication that an increase in inlet concentration of these compounds would not have any major effect on their removal. Figures 3 through 5 represent the removal of nonhalgenated VOCs in BF for Phase I of this study.

3.2.1.1.2 Halogenated VOCs

With the addition of gasoline, The average removal efficiencies for dichlorobenzene (25.5%) and methylene chloride (76.1%) increased significantly. Still no removal was observed for tetrachloroethylene and chloroform. It should be reminded that the addition of gasoline has no effect in inlet concentration. Figures 6 through 9 represent the removal of halgenated VOCs in BF for Phase I of this study.

3.2.1.2 Biotickling Filter

3.2.1.2.1 Nonhalogenated VOCs

With the gasoline addition, the removal efficiencies for nonhalogenated VOCs are still poor. Attempt was made to control the pH from within the range of 1-2 to the neutral pH (7-8) for the last week of October for BTF. Although there was a slight improvement, but overall the removal efficiency did not change. Figures 10 through 12 represent the removal of nonhalgenated VOCs in BTF for Phase I of this study.

3.2.1.2.2 Halogenated VOCs

With the gasoline addition, the removal efficiencies for halogenated VOCs are still poor. Attempt was made to control the pH from within the range of 1-2 to the neutral pH (7-8) for the last week of October for BTF. Although there was a slight improvement, but overall the removal efficiency did not change. Figures 13 through 16 represent the removal of halgenated VOCs in BTF for Phase I of this study.

3.2.2 Phase II: Volatile Organic Compounds (VOCs) Removal (November 2000)

3.2.2.1 Biofilter

At this phase of study with the addition of gasoline with the rate of 50 μl / second, a mixture of solution of methylene chloride and trichloroethylene (TCE) was added to the inlet of both BF and BTF with the rate of 25 μl / second. The following shows the result at this phase of study.

3.2.2.1.1 Nonhalogenated VOCs

With the addition of gasoline and Mixture, the removal of non-halogenated VOCs for BF were decreased. The average removal efficiencies for BTX were 17, 26 and 40 respectively. However, during the second week (11/13- 11/15), a small decrease was observed in BTX removal. These trends are shown for BTX graphs for biofilter. These results indicate that the addition of Mixture has poisoned the bacteria responsible for biodegradation of BTX compounds. Figures 17 through 19 represent the removal of nonhalgenated VOCs in BF for Phase II of this study.

3.2.2.1.2 Halogenated VOCs

With the addition of gasoline and Mixture, the average removal efficiencies for all of these compounds decreased drastically. This is probably due to the same effects as mentioned before. Figures 20 through 23 represent the removal of halgenated VOCs in BF for Phase II of this study.

3.2.2.2 Biotrickling Filter

3.2.2.2.1 Nonhalogenated VOCs

With the gasoline addition and Mixture, the removal efficiencies for nonhalogenated VOCs are still poor. Attempt was made to control the pH from within the range of 1-2 to the neutral pH (7-8) for the last week of October for BTF. Although there was a slight improvement, but overall the removal efficiency did not change. Figures 24 through 26 represent the removal of nonhalgenated VOCs in BTF for Phase II of this study.

3.2.2.2.2 Halogenated VOCs

With the gasoline addition and Mixture, the removal efficiencies for halogenated VOCs did not alter at all. Figures 27 through 30 represent the removal of halgenated VOCs in BTF for Phase II of this study.

3.2.3 Phase III: Odor, Hydrogen Sulfide, Organic Sulfur Compounds, and Volatile Organic Compounds (VOCs) Removal, December 2000

At this phase of study, the gasoline and Mixture injection was stopped and both systems return to normal operation. Based on the recommendation by WERF committee and also to fullfil the requirement set by South Coast Air Quality Management District (SCAQMD) on Research Permit issued to BF, the series of testing were performed in both BF and BTF. The target constituents were hydrogen sulfide, odor, organic sulfur compounds (mercaptans), and VOCs. Performance Analytical Laboratories (PAL) performed the analyses of hydrogen sulfide and mercaptans. The Odor panel analyses conducted by Odor Science & Engineering, Inc. (OS&E). Upon the arrival the samples were analyzed by dynamic dilution olfactometry using a trained and screened odor paned of 8 members. The samples were quantified in terms of dilution-to-threshold (D/T) ratio and odor intensity in accordance with ASTM Methods E-679-91 and E-544-99, respectively. The odor panelists were asked to describe the odor character of the samples at varying dilution levels. The removal efficiencies for odor and hydrogen sulfide are 98 to 100% respectively. . The removal efficiencies for other mercaptans are varying. No conclusion can be made for removal of other mercaptans. Figures 45 and 51 represent the odor removal for BF and BTF taken on 13 December of 2000. Figures 46 through 50 represent the removal of mercaptans for BF taken on 13 December of 2000. Figures 52 through 56 represent the removal of mercaptans for BTF taken on 13 December of 2000.

3.2.3.1 Biofilter

3.2.3.1.1 Biofilter-Nonhalogenated VOCs

The removal of non-halogenated VOCs for BF was increased. The average removal efficiencies for benzene, toluene and total xylenes were 44, 71 and 50 respectively. Figures 31 through 33 represent the removal of nonhalgenated VOCs in BF for Phase III of this study.

3.2.3.1.2 Biofilter-Halogenated VOCs

The average removal efficiencies for all of these compounds return to normal condition. The removals for dichlorobenzene still high (50%) but the removal for methylene chloride decreased. This is probably due to stabilization time for bacteria after Mixture addition. Figures 34 through 37 represent the removal of halgenated VOCs in BF for Phase III of this study.

3.2.3.2 Biotrickling Filter

3.2.3.2.1 Biotrickling Filter -Nonhalogenated VOCs

The removal efficiencies for nonhalogenated VOCs are still poor. Effectively no removal was observed later in BTF. Figures 38 through 40 represent the removal of nonhalgenated VOCs in BTF for Phase III of this study.

3.2.3.2.2 Biotrickling Filter-Halogenated VOCs

The removal efficiencies for halogenated VOCs did not alter at all and still remains poor. Figures 41 through 44 represent the removal of halgenated VOCs in BTF for Phase III of this study.

4. CONCLUSIONS

The overall results indicate that in spite of large increase in VOCs concentration, the BF performance remains the same as for natural VOCs concentration at headworks. This shows any upset or shock in influent concentration of VOCs in HTP plant does not have any major effect on BF removal. At this time, we are in a good situation to evaluate the BTF performance. As mentioned, the change in concentration of BTX compounds did not have any effect for their removal. As mentioned in Section 6 of Interim Report, perhaps it is appropriate to stimulate the VOCs removal. To both systems specific bacteria should be added that are specialized in VOCs removal.

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5.2 Biotrickling filter

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Figure I. Long Term Performance of H2S Removal in Biofilter

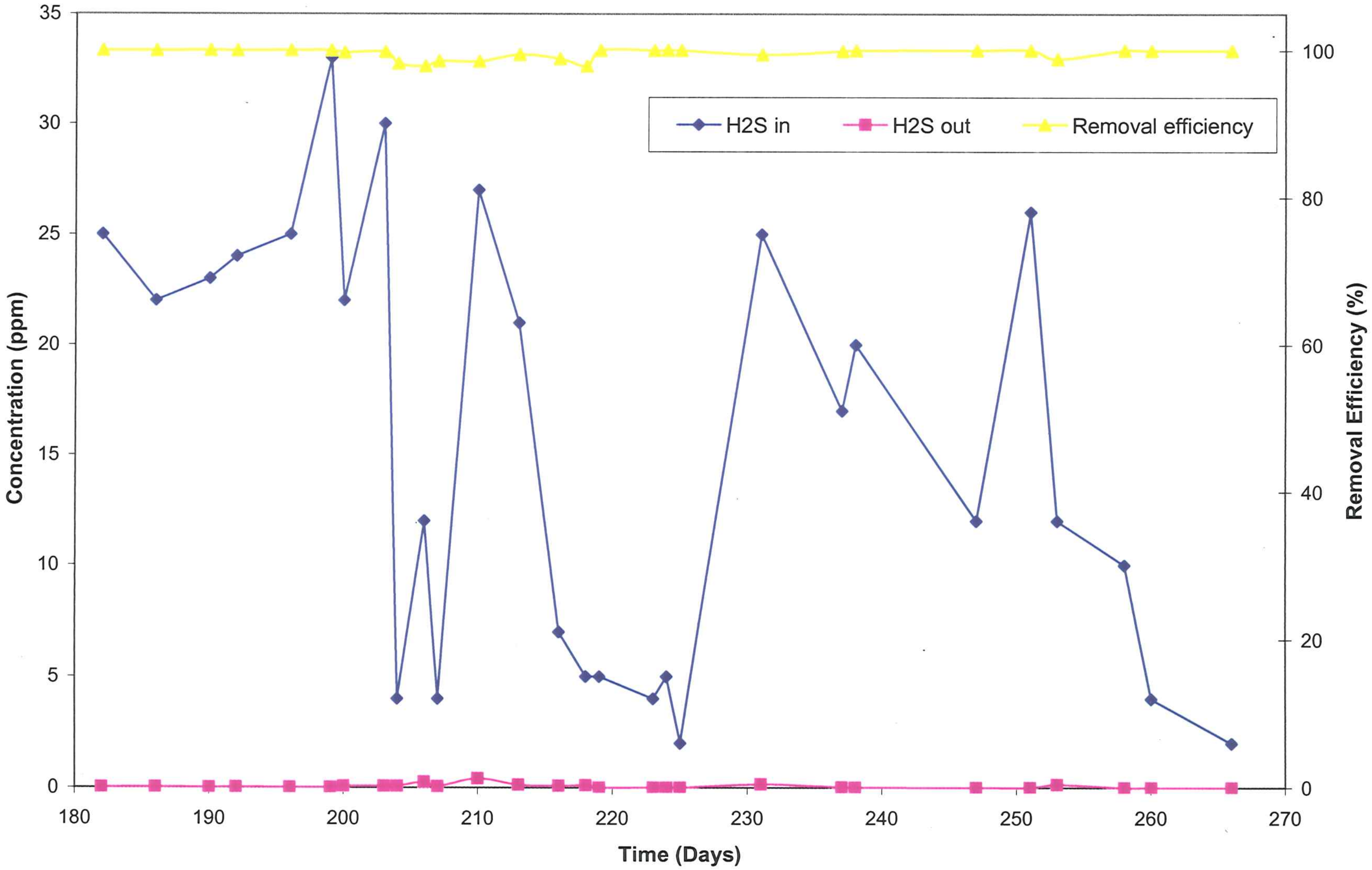
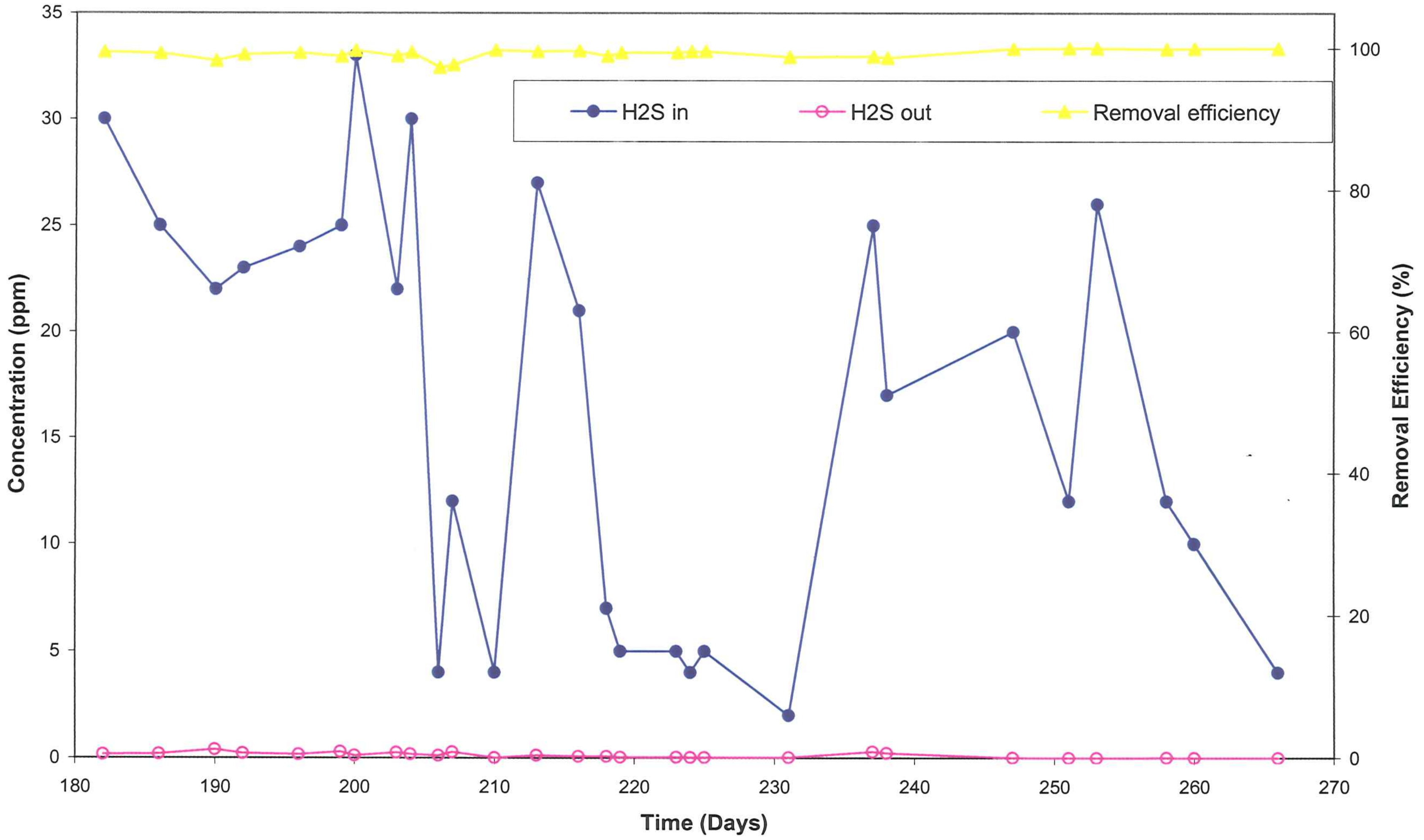


Figure 2. Long Term Performance of H2S Removal in Biotrickling Filter



PHASE I

VOCs FIGURES

Figure 3. Removal of VOCs in Biofilter, Benzene (Phase I)

Gasoline injection (50μl / second)

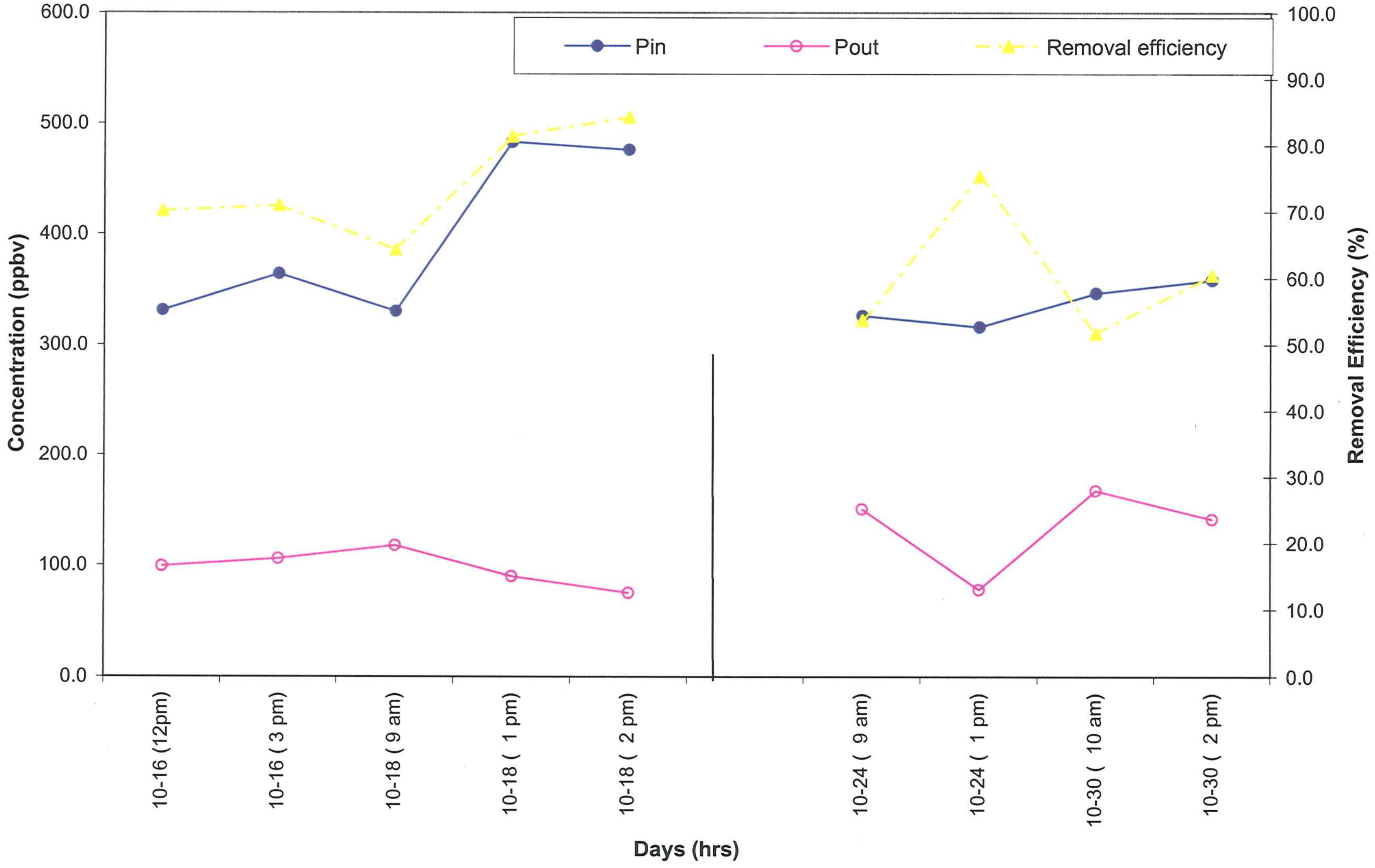


Figure 4. Removal of VOCs in Biofilter , Toluene (Phase I)

Gasoline injection (50μl / second)

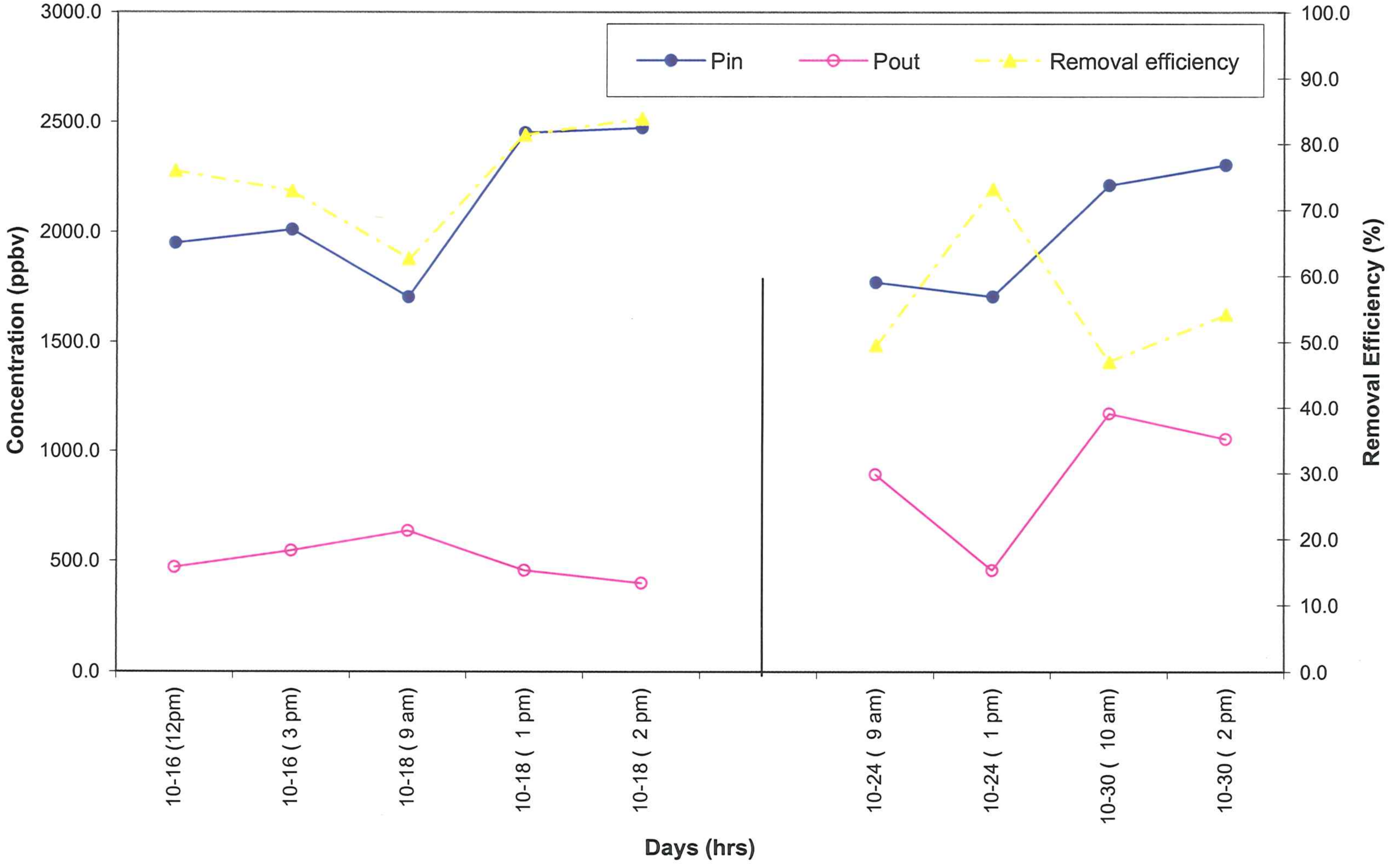


Figure 5. Removal of VOCs in Biofilter, Total Xylenes (Phase I)

Gasoline injection (50μl / second)

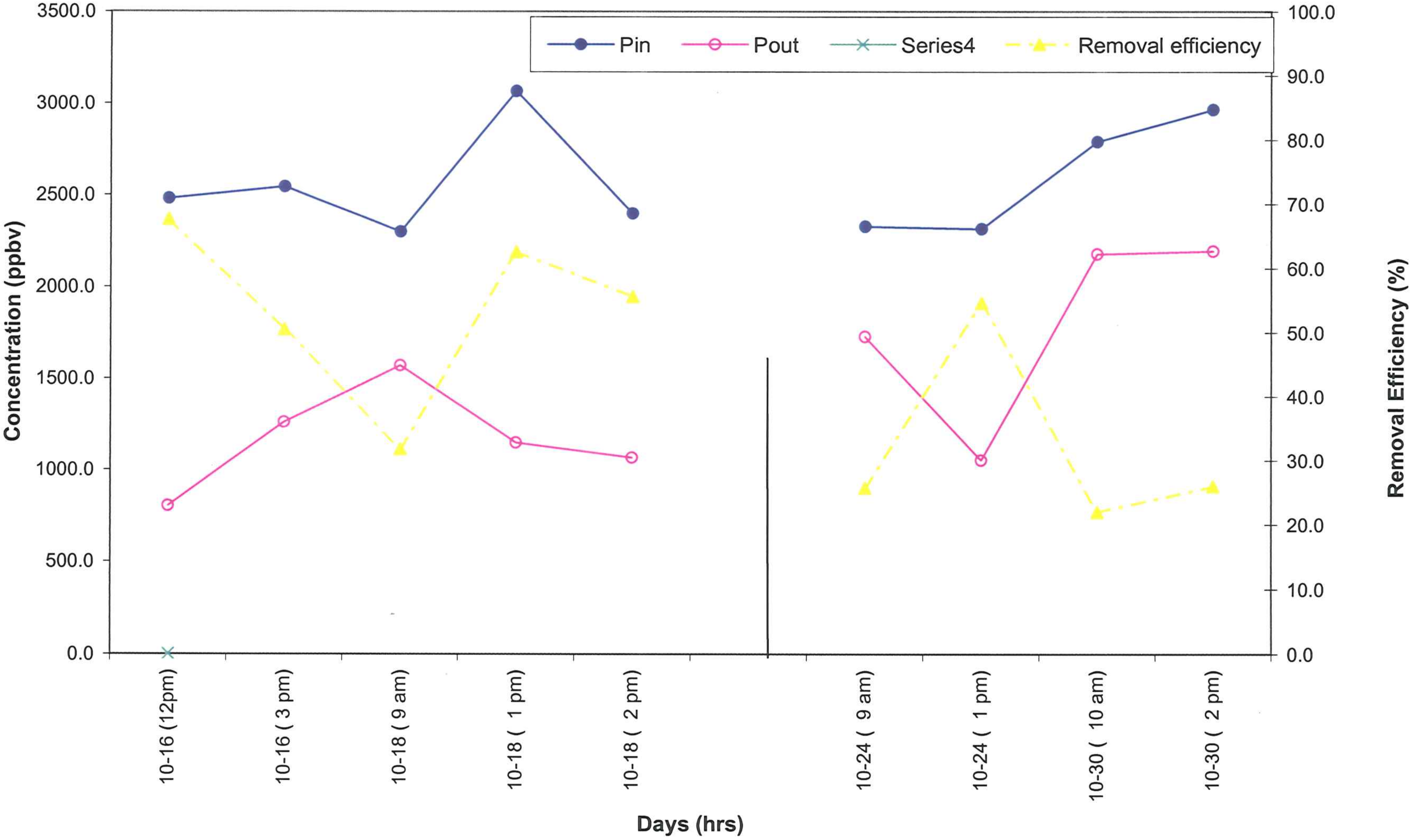


Figure 6. Removal of VOCs in Biofilter, Dichlorobenzene (Phase I)

Gasoline injection (50μl / second)

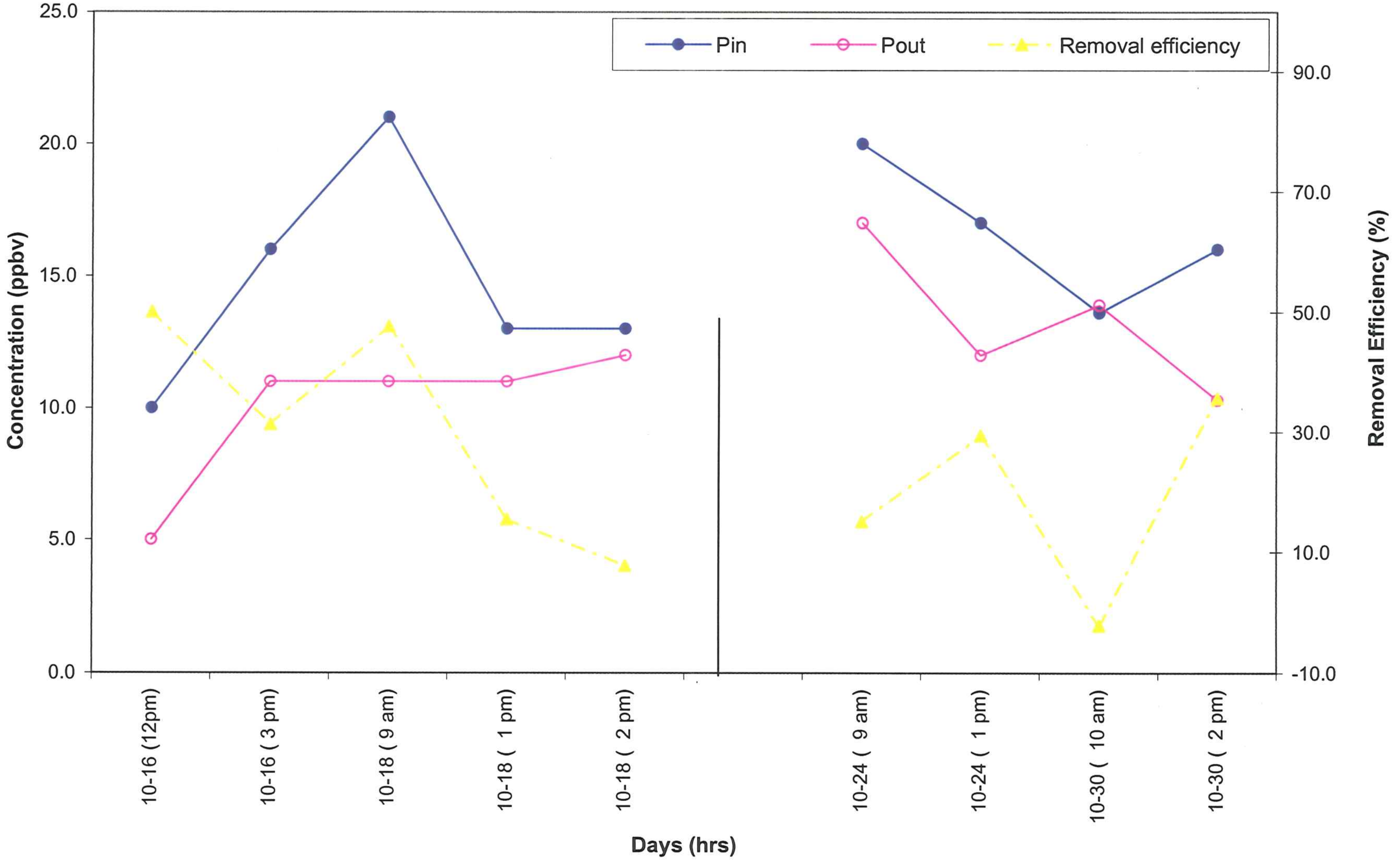


Figure 7. Removal of VOCs in Biofilter, Methylene Chloride (Phase I)
Gasoline injection (50μl / second)

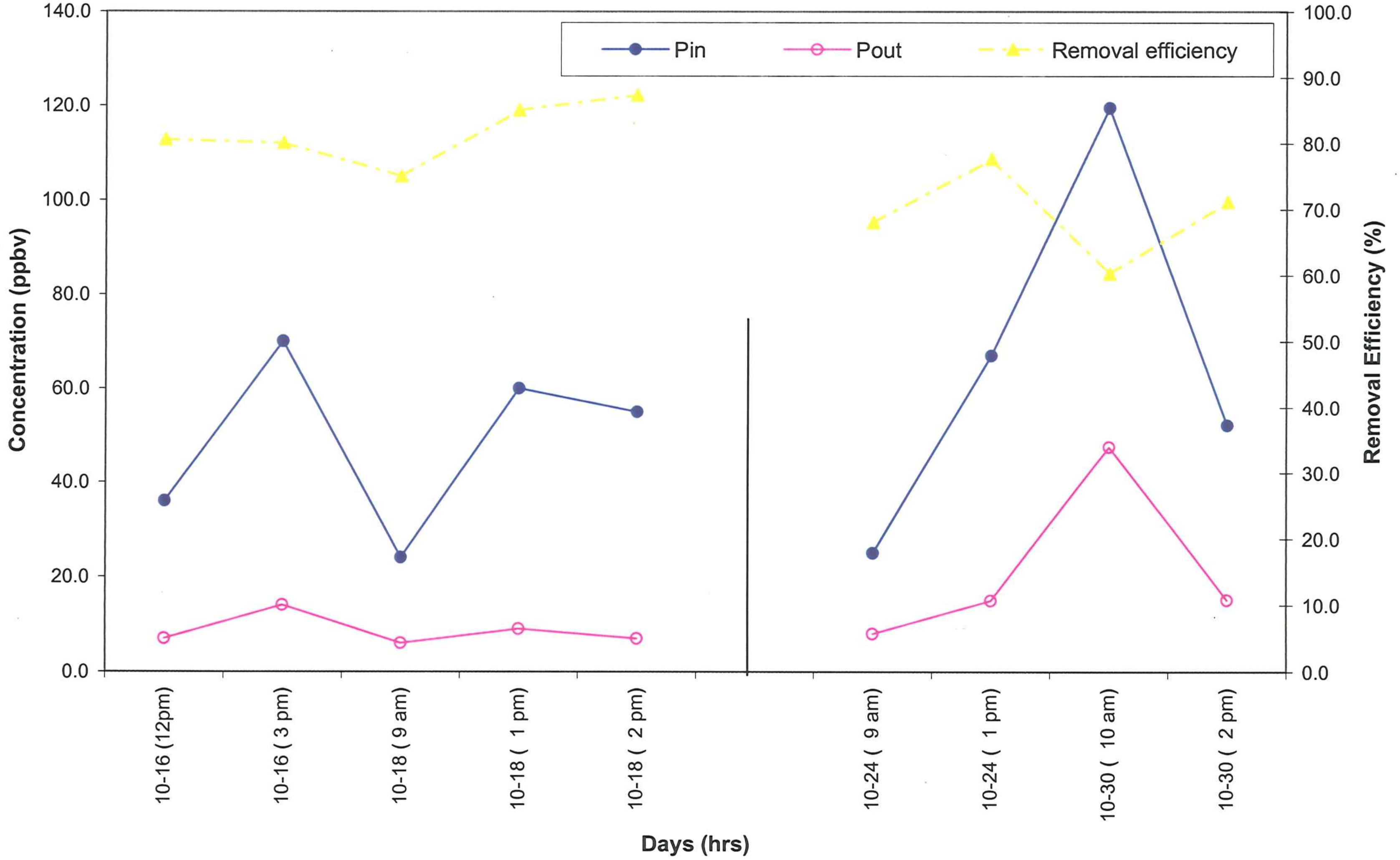


Figure 8. Removal of VOCs in Biofilter, Chloroform (Phase I)

Gasoline injection (50μl / second)

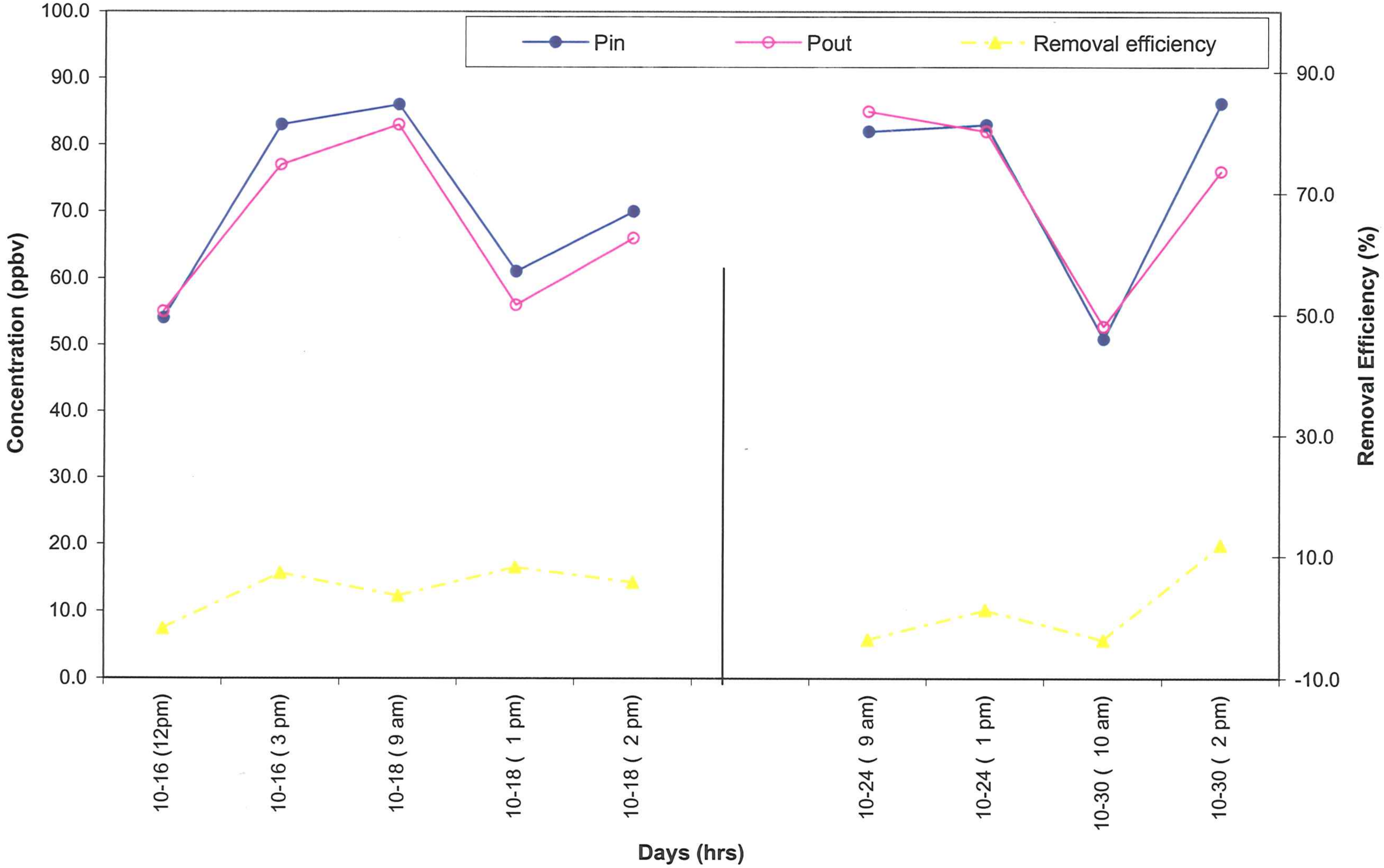


Figure 9. Removal of VOCs in Biofilter, Tetrachoroethylene (Phase I)

Gasoline injection (50μl / second)

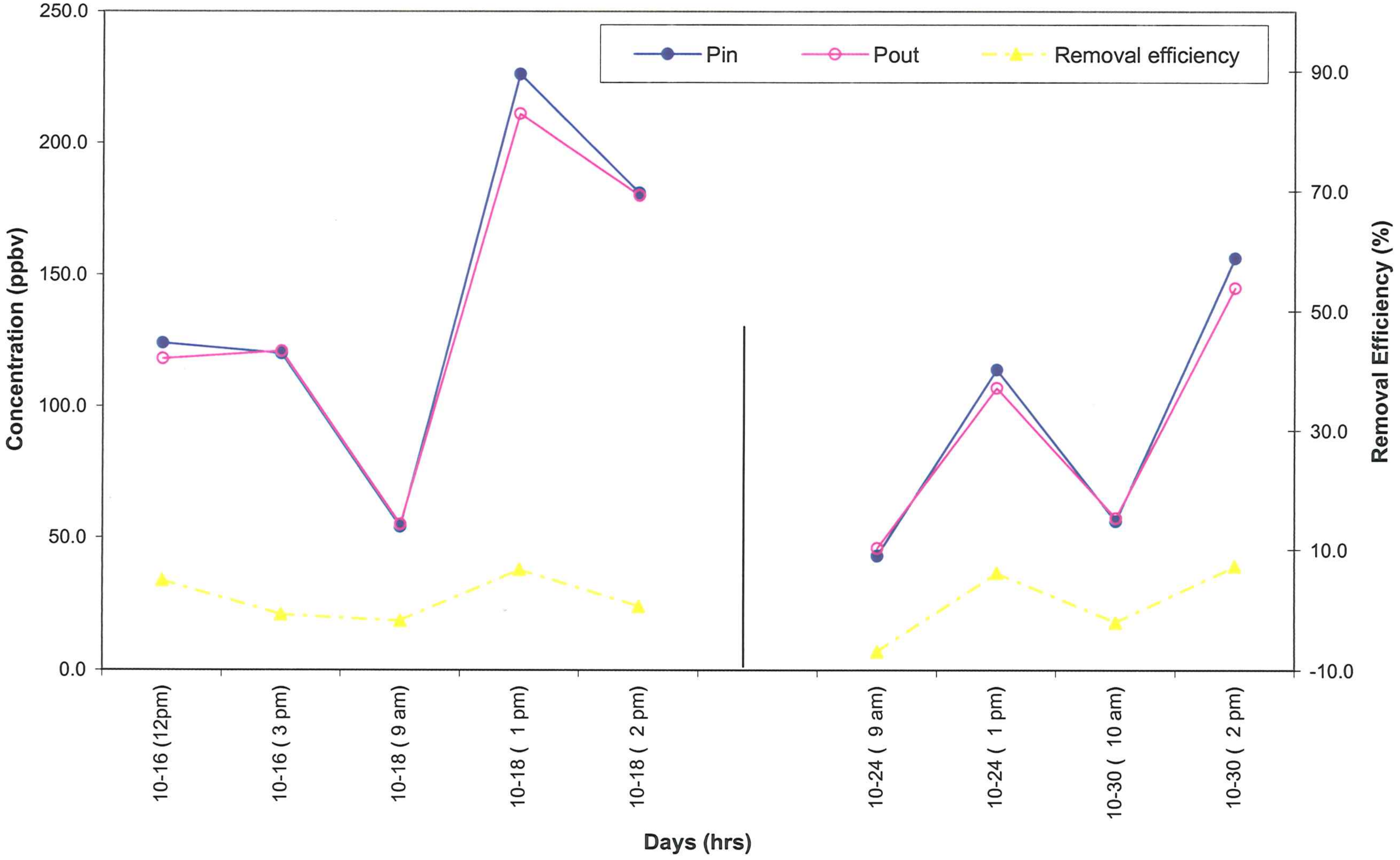


Figure 10. Removal of VOCs in Biotrickling Filter, Benzene (Phase I)

Gasoline injection (50μl / second)

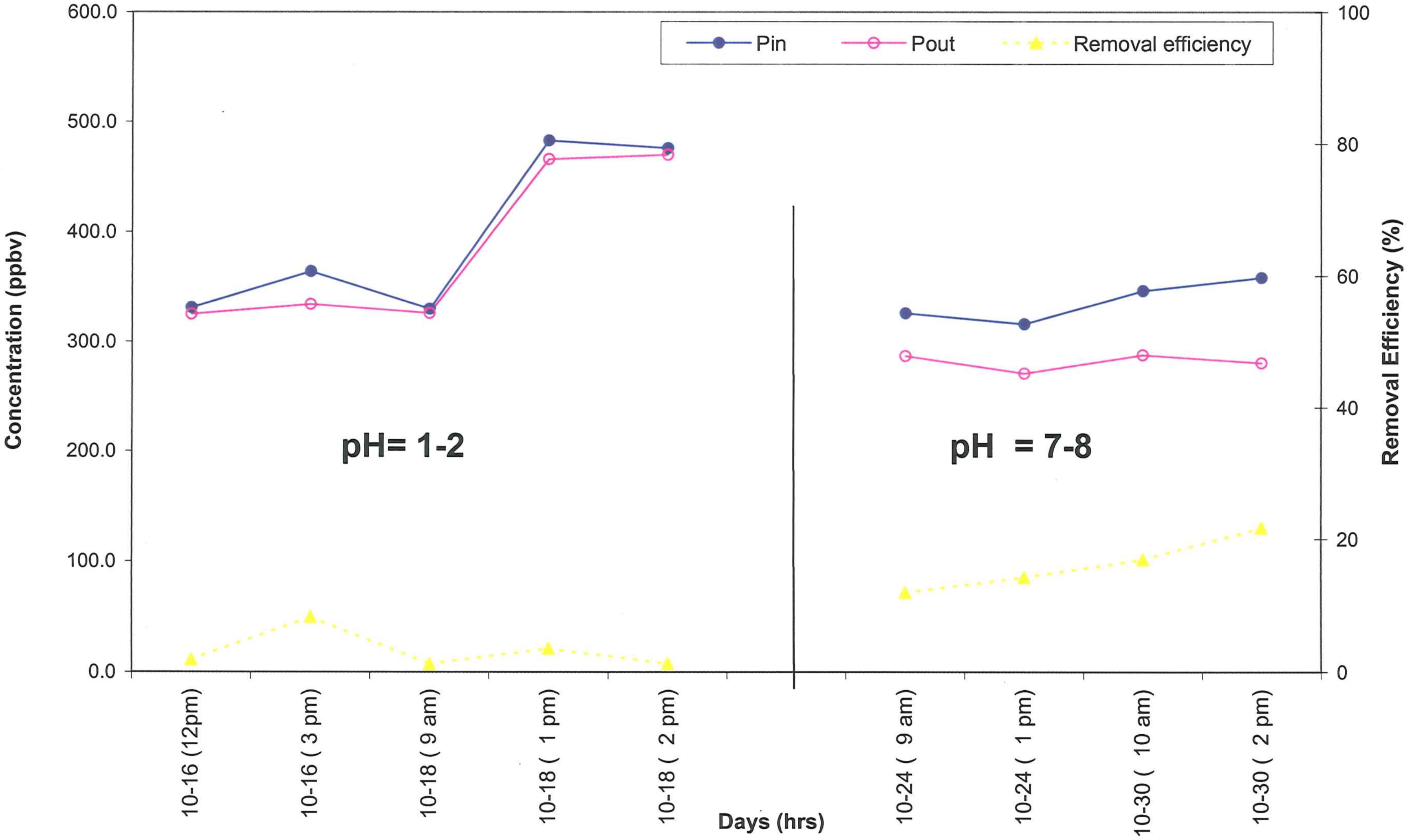


Figure 11. Removal of VOCs in Biotrickling Filter, Toluene

Gasoline injection rate (50μl / second)

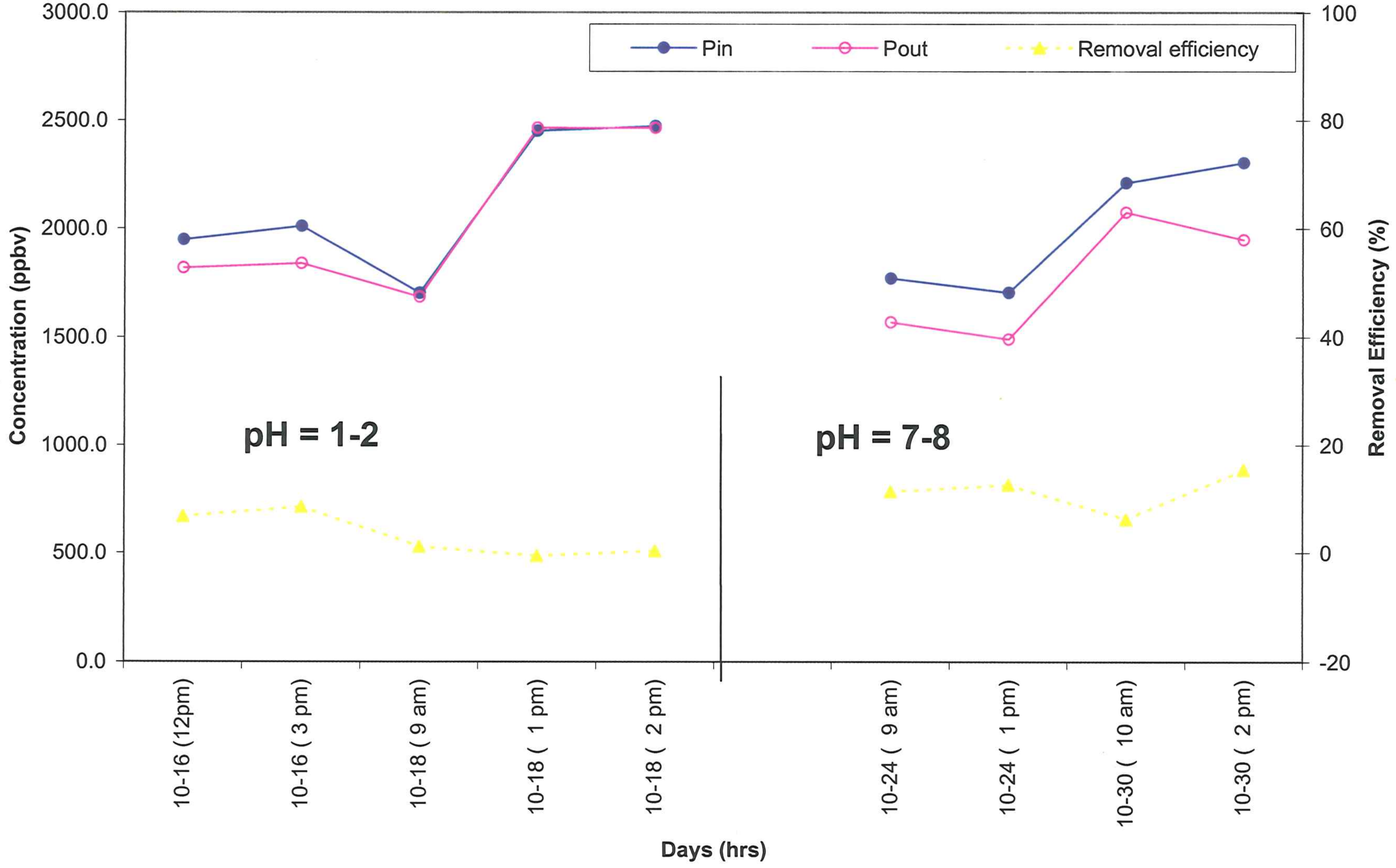


Figure 12. Removal of VOCs in Biotrickling Filter, Total Xylenes (Phase I)

Gasoline injection (50μl / second)

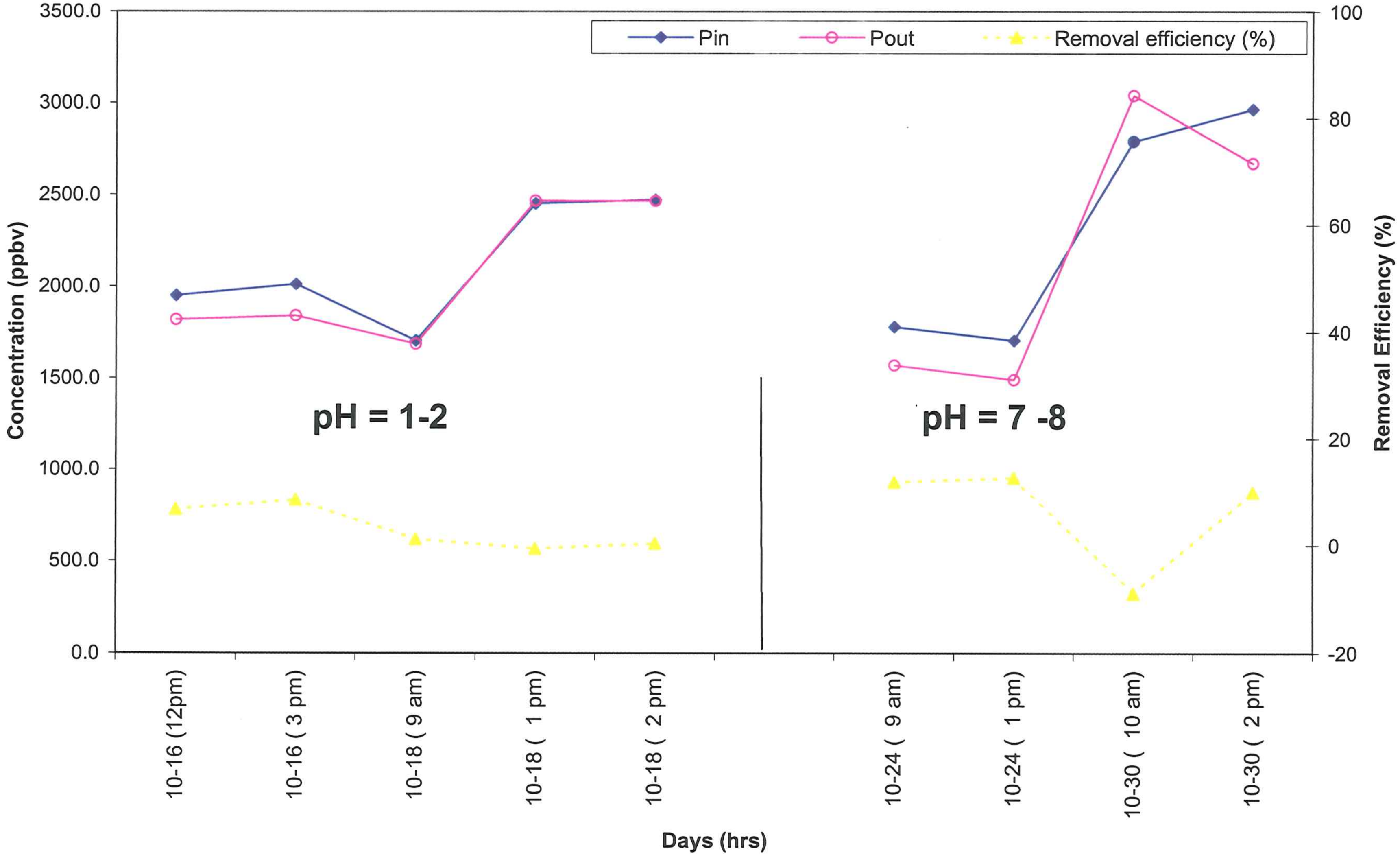


Figure 13. Removal of VOCs in Biotrickling Filter, Dichlorobenzene (Phase I)

Gasoline injection (50μl / second)

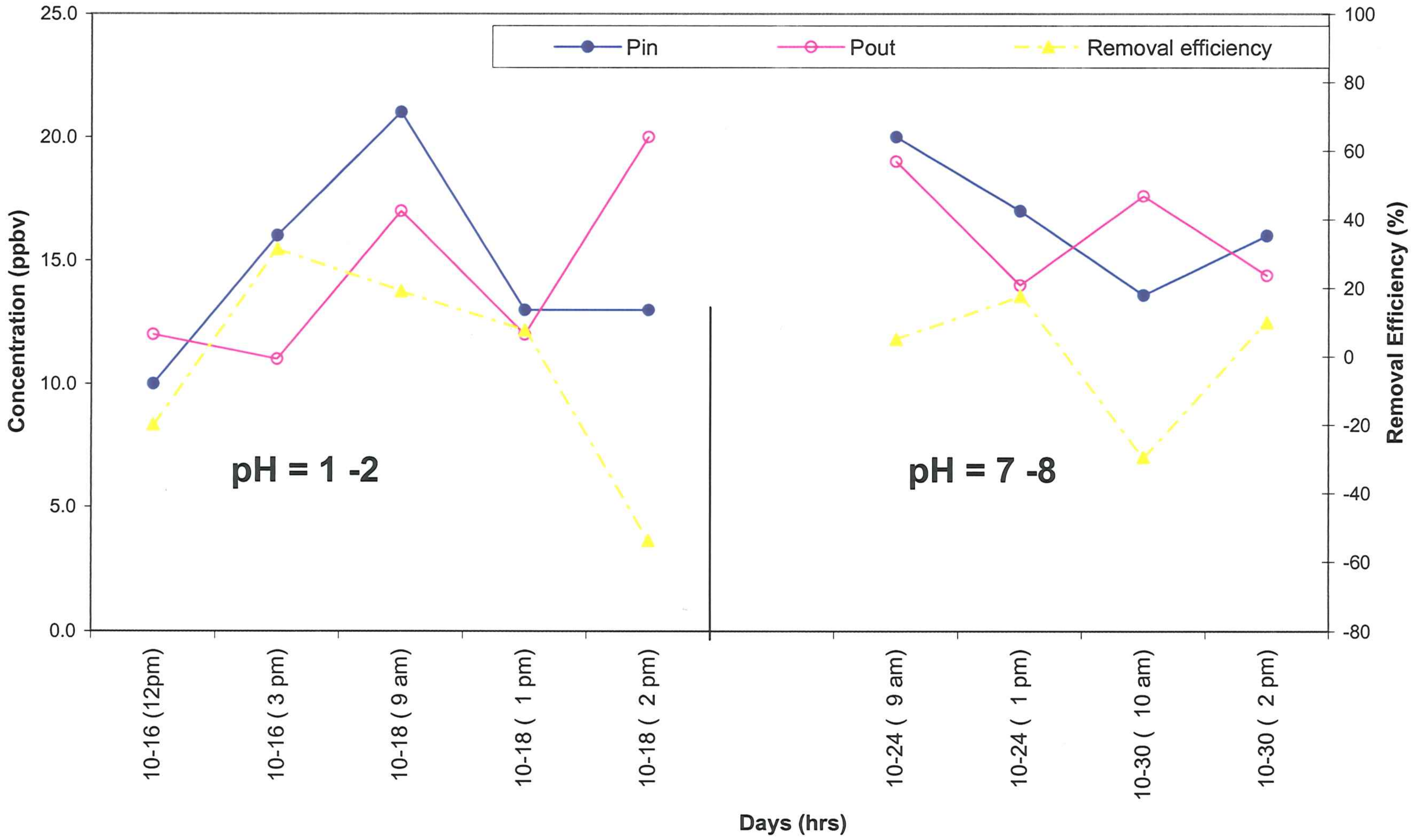


Figure 14. Removal of VOCs in Biotrickling Filter, Methylene Chloride (Phase I)
Gasoline injection (50μl / second)

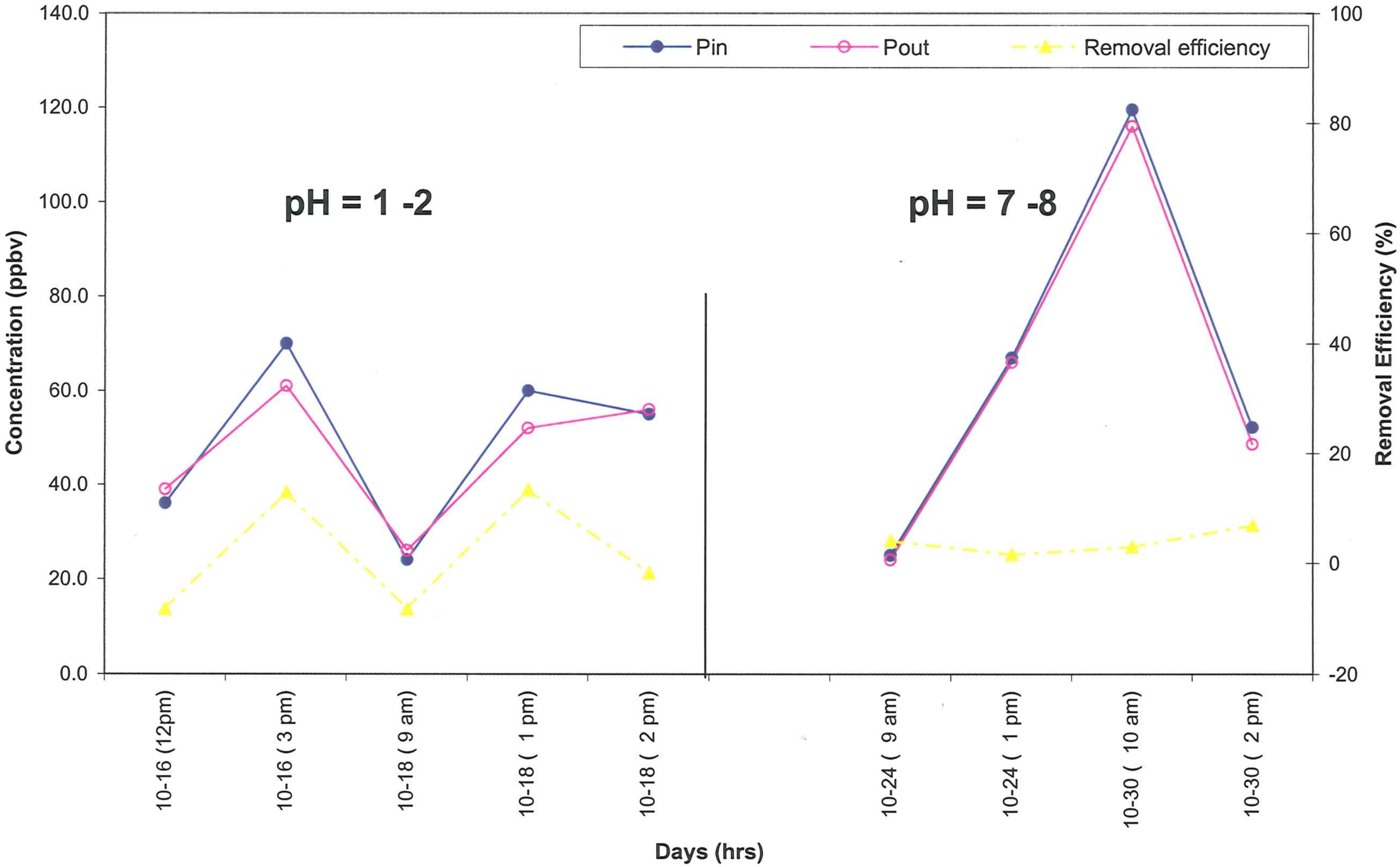


Figure 15. Removal of VOCs in Biotrickling Filter, Chloroform (Phase I)

Gasoline injection (50μl / second)

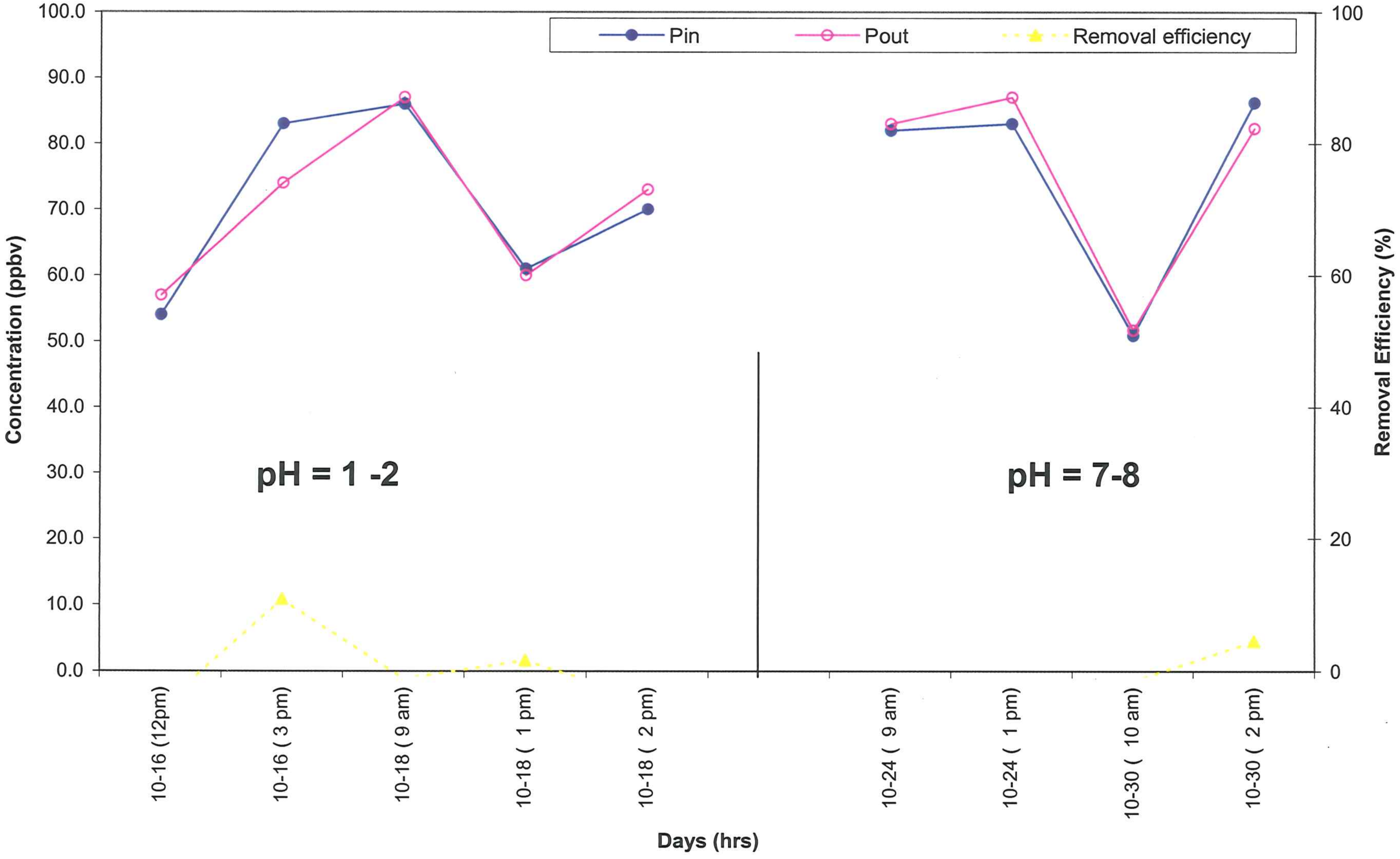
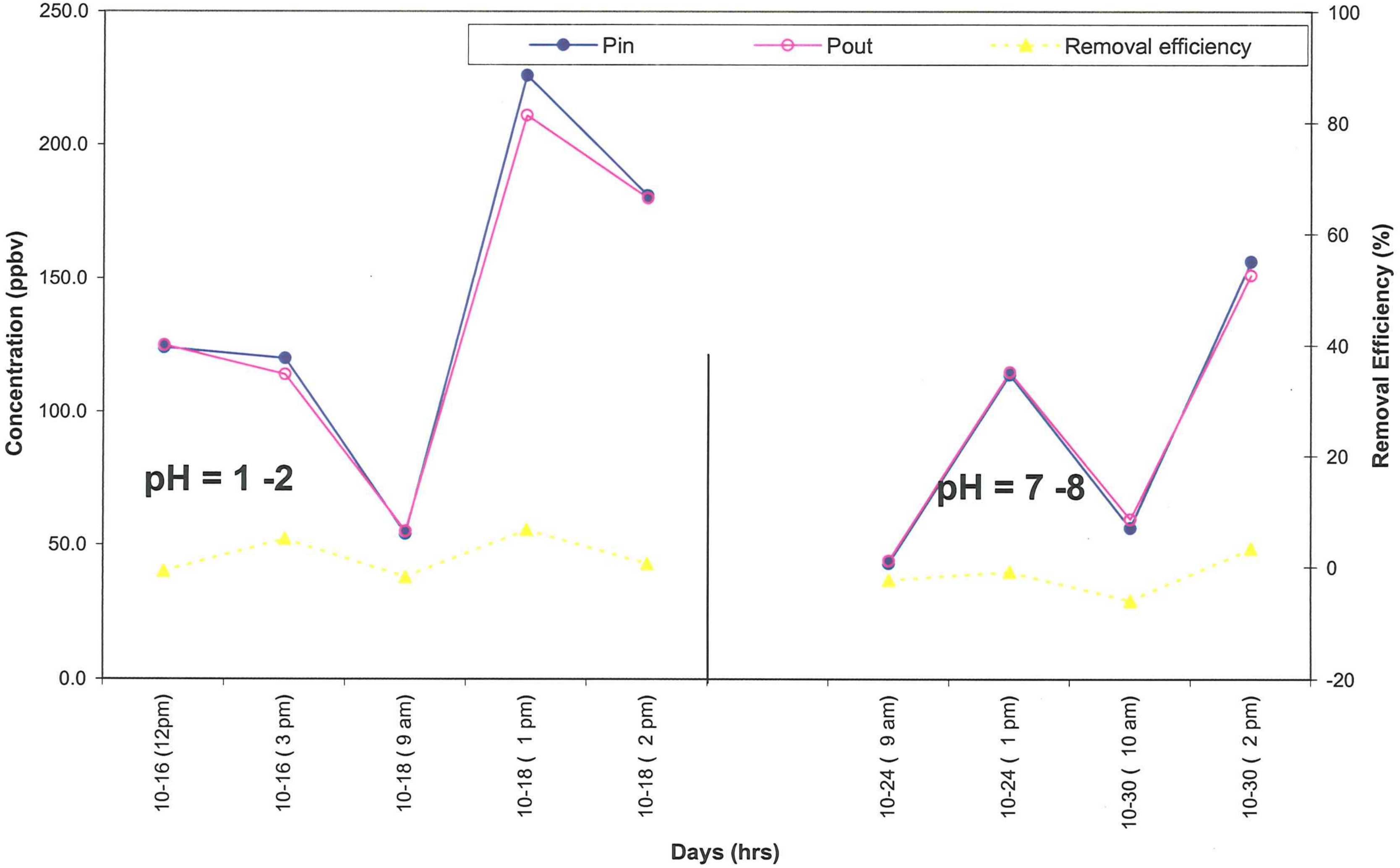


Figure 16. Removal of VOCs in Biotrickling Filter, Tetrachloroethylene (Phase I)

Gasoline injection (50μl / second)



PHASE II

VOCs FIGURES

Figure 17. Removal of VOC's in Biofilter - Benzene (Phase II)
Gasoline injection (50μl / second) and
mixture of methylene chloride &TCE injection (25 μl / second)

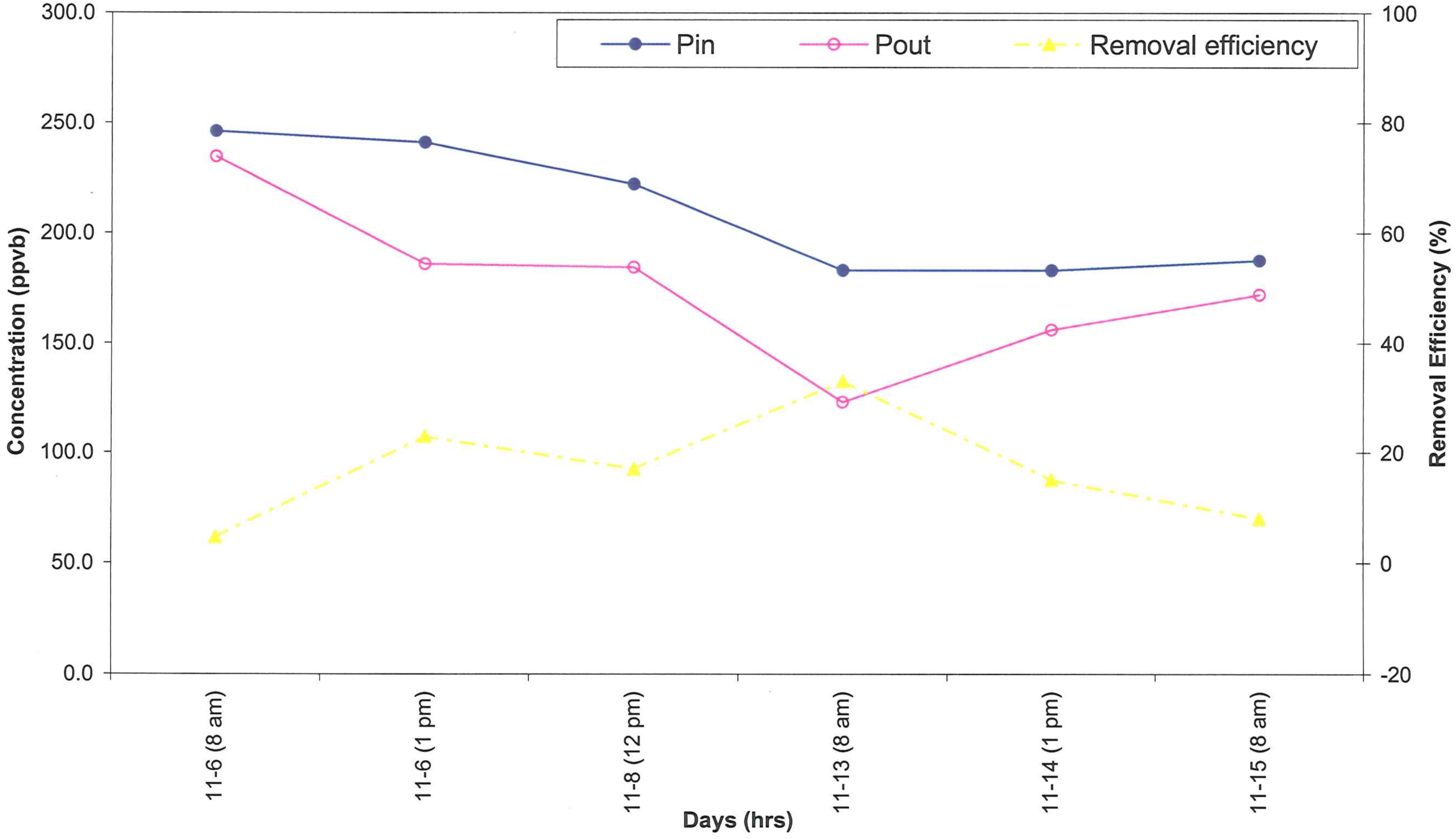


Figure 18. Removal of VOC's in Biofilter - Toluene (Phase II)

Gasoline injection (50μl / second) and
mixture of methylene chloride &TCE injection (25 μl / second)

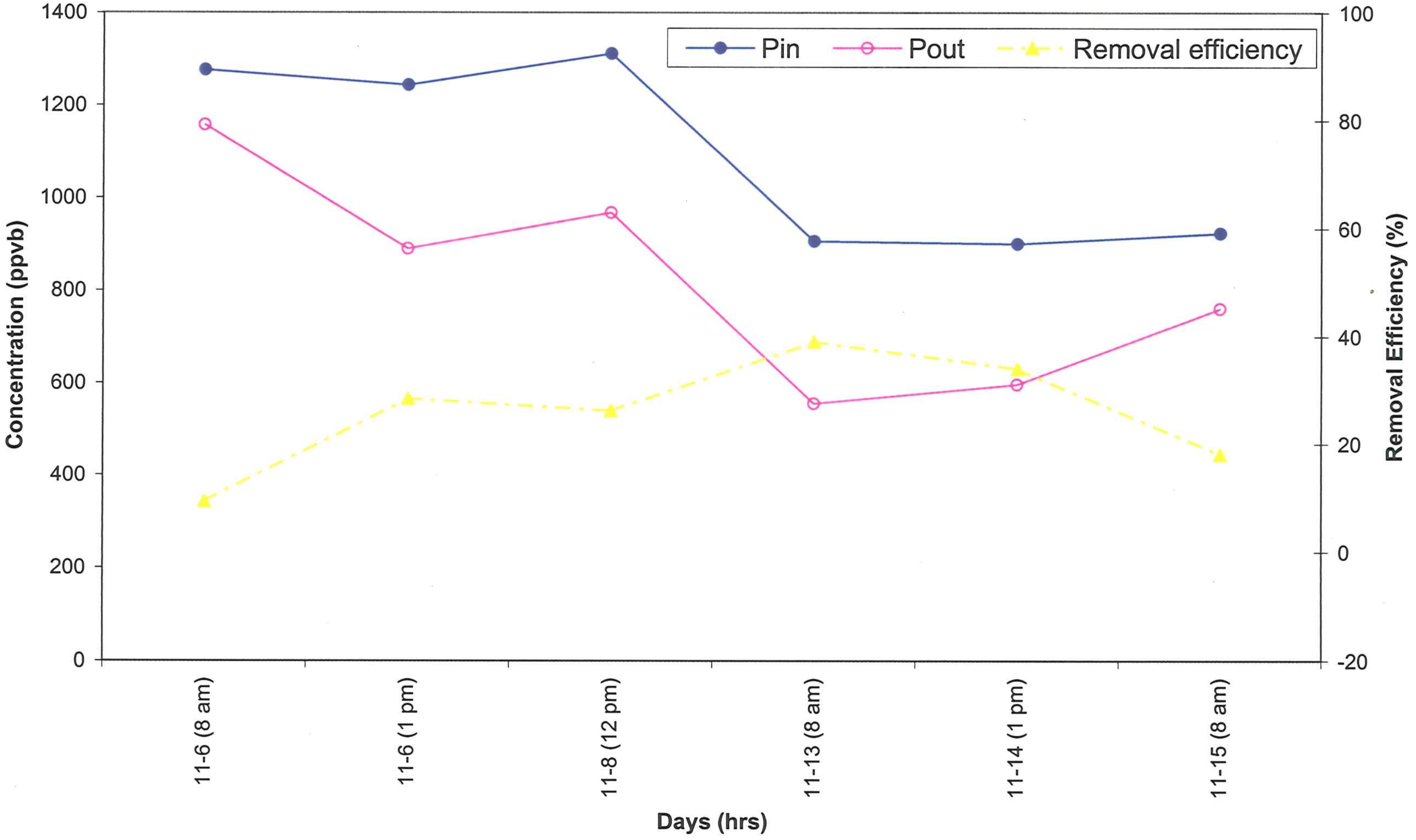


Figure 19. Removal of VOC's in Biofilter - Total Xylenes (Phase II)

Gasoline injection (50μl / second) and mixture of methylene chloride &TCE injection (25 μl / second)

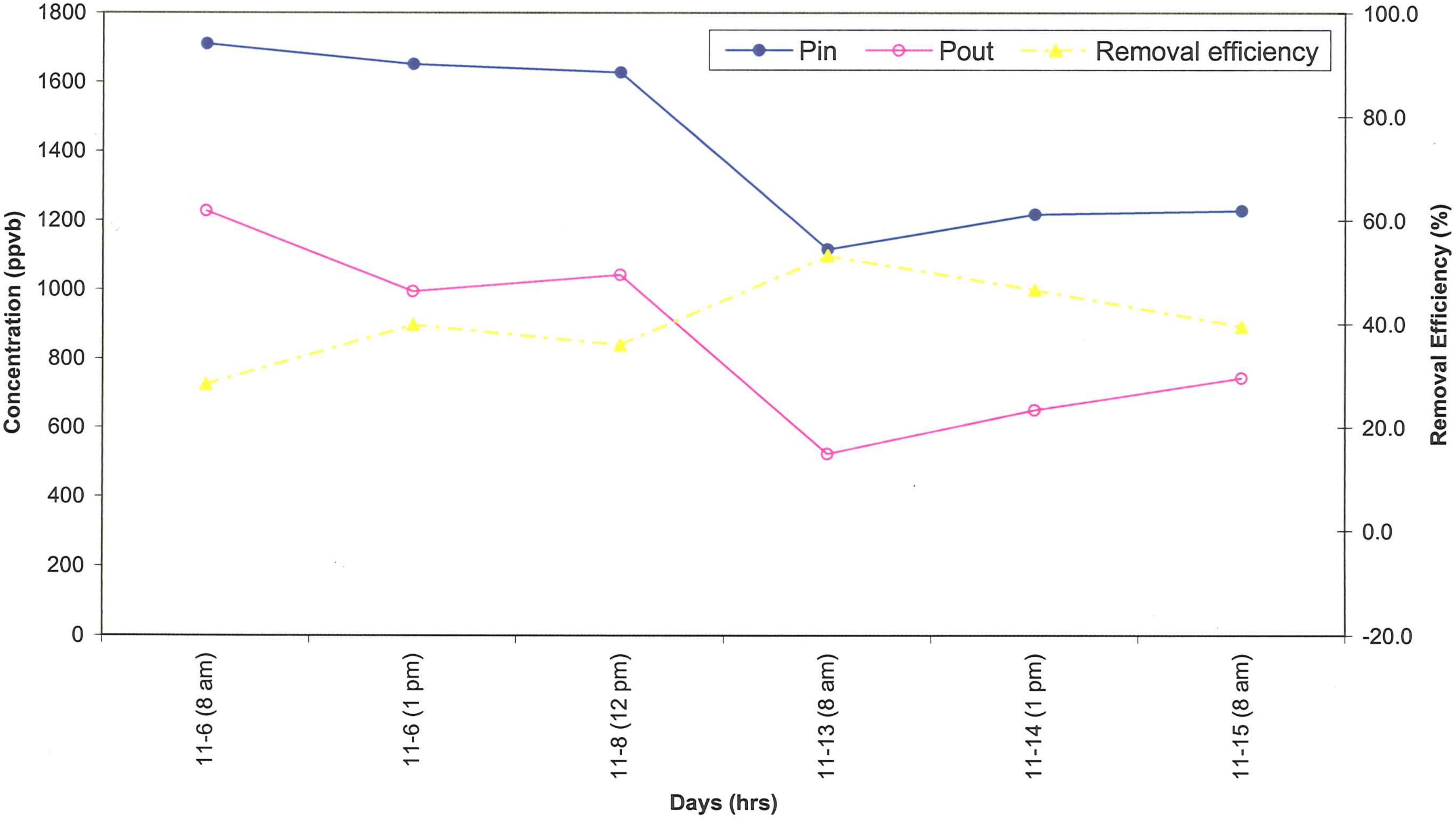


Figure 20. Removal of VOC's in Biofilter - Dichlorobenzene (Phase II)

Gasoline injection (50μl / second) and
mixture of methylene chloride &TCE injection (25 μl / second)

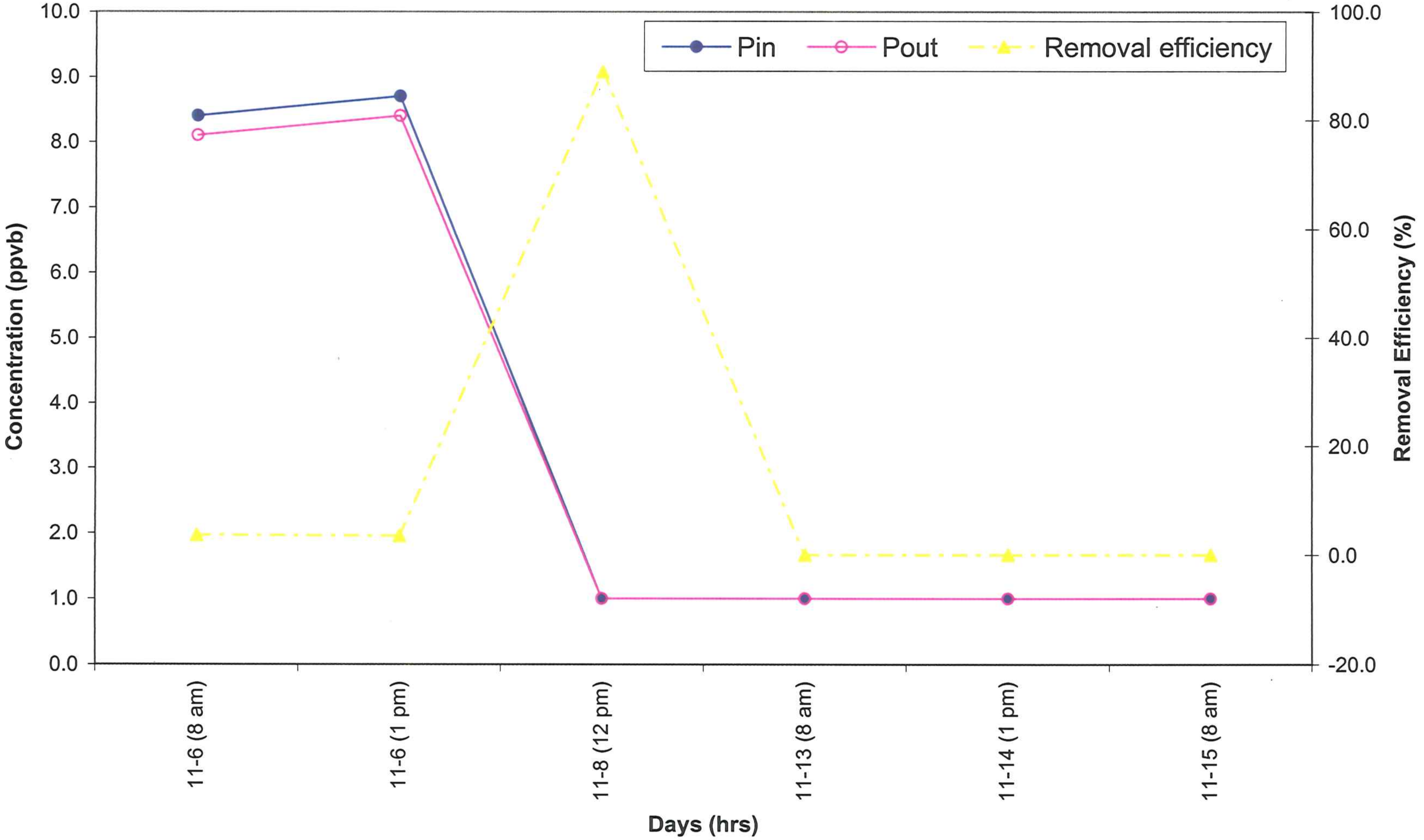


Figure 21. Removal of VOC's in Biofilter - Methylene Chloride (Phase II)

Gasoline injection (50μl / second) and
mixture of methylene chloride &TCE injection (25 μl / second)

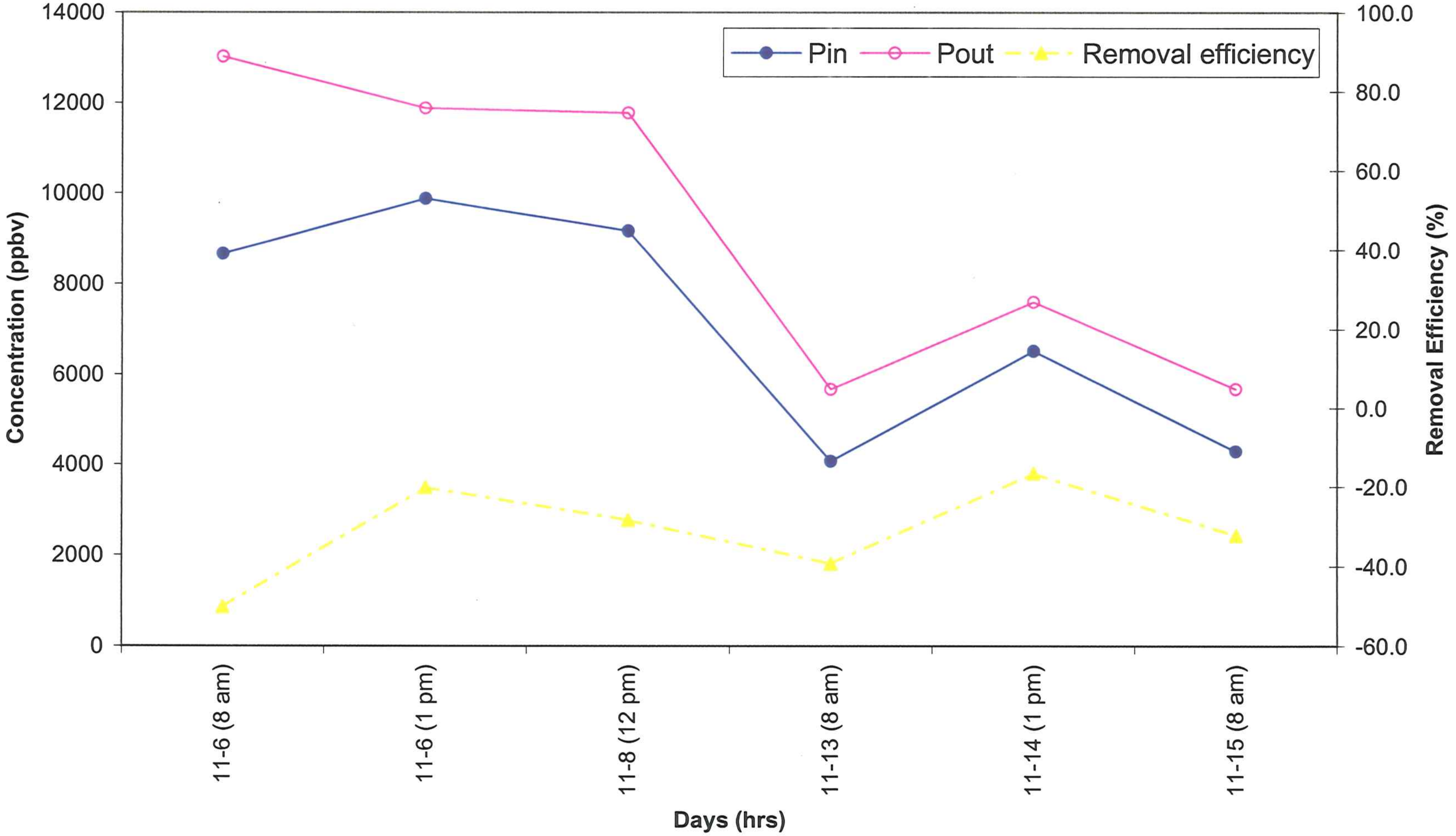


Figure 22. Removal of VOC's in Biofilter - Chloroform (phase II)

Gasoline injection (50μl / second) and
mixture of methylene chloride &TCE injection (25 μl / second)

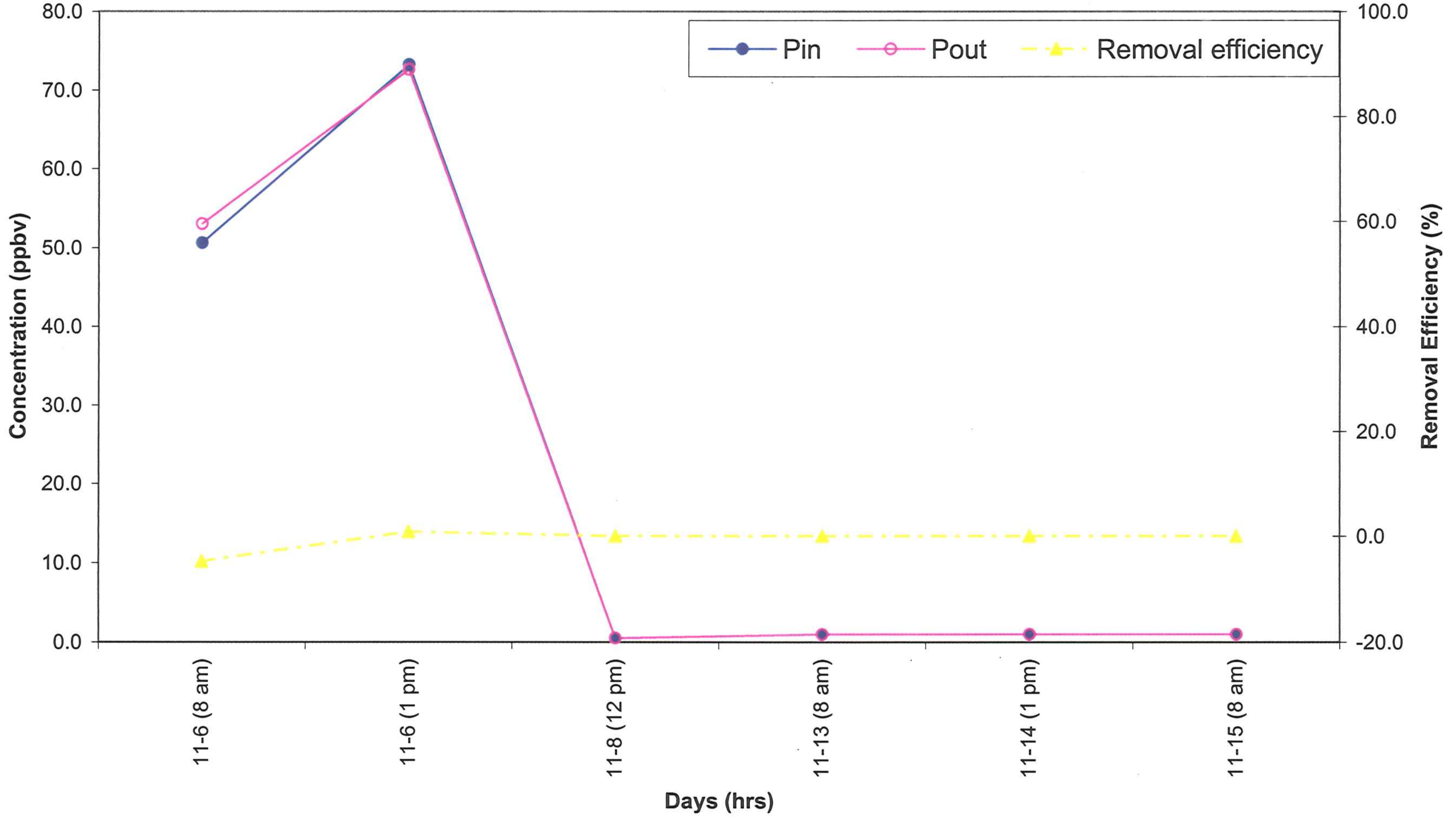


Figure 23. Removal of VOC's in Biofilter - Tetrachloroethylene (PhaseII)

Gasoline injection (50μl / second) and
mixture of methylene chloride,&TCE injection (25 μl / second)

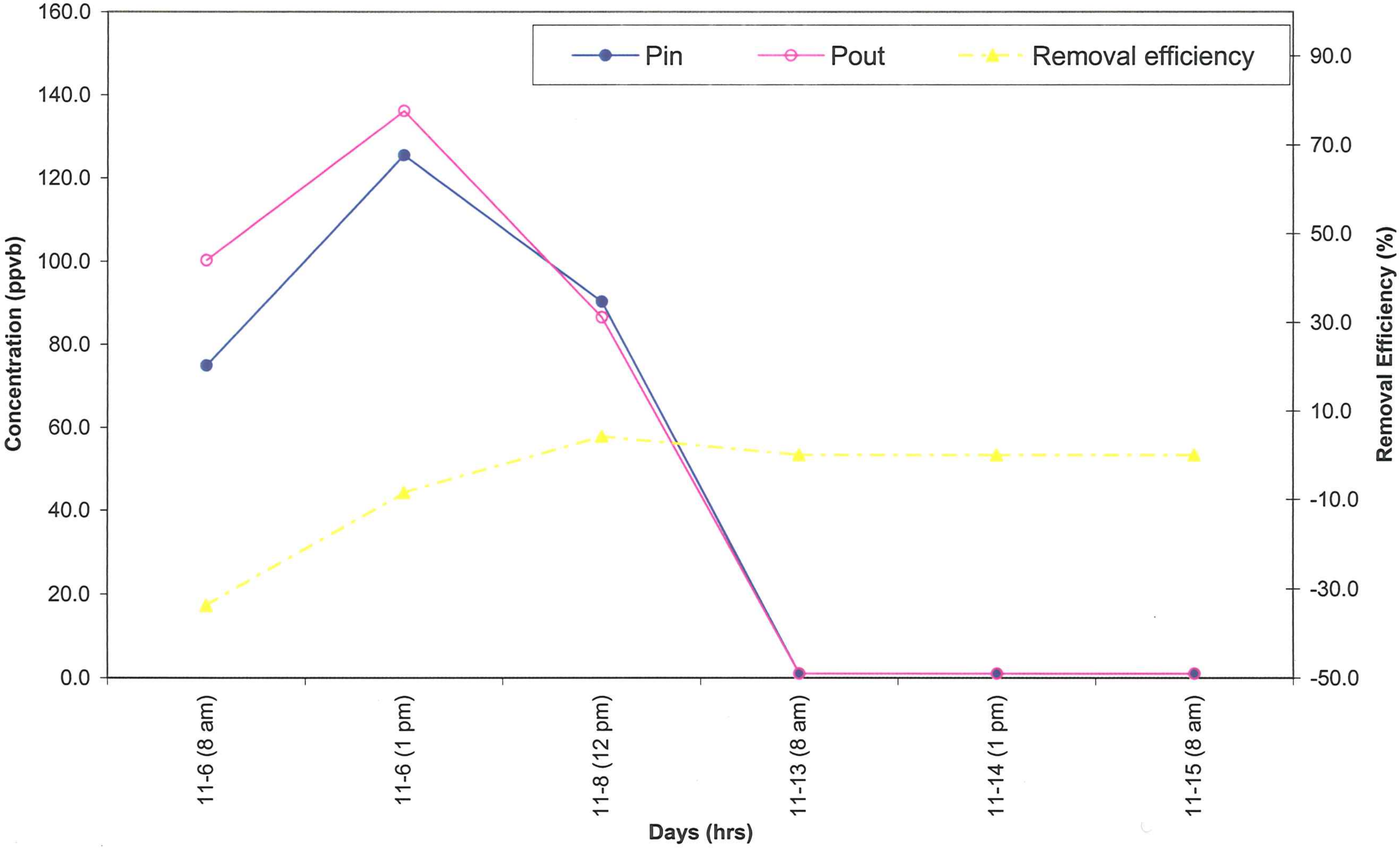
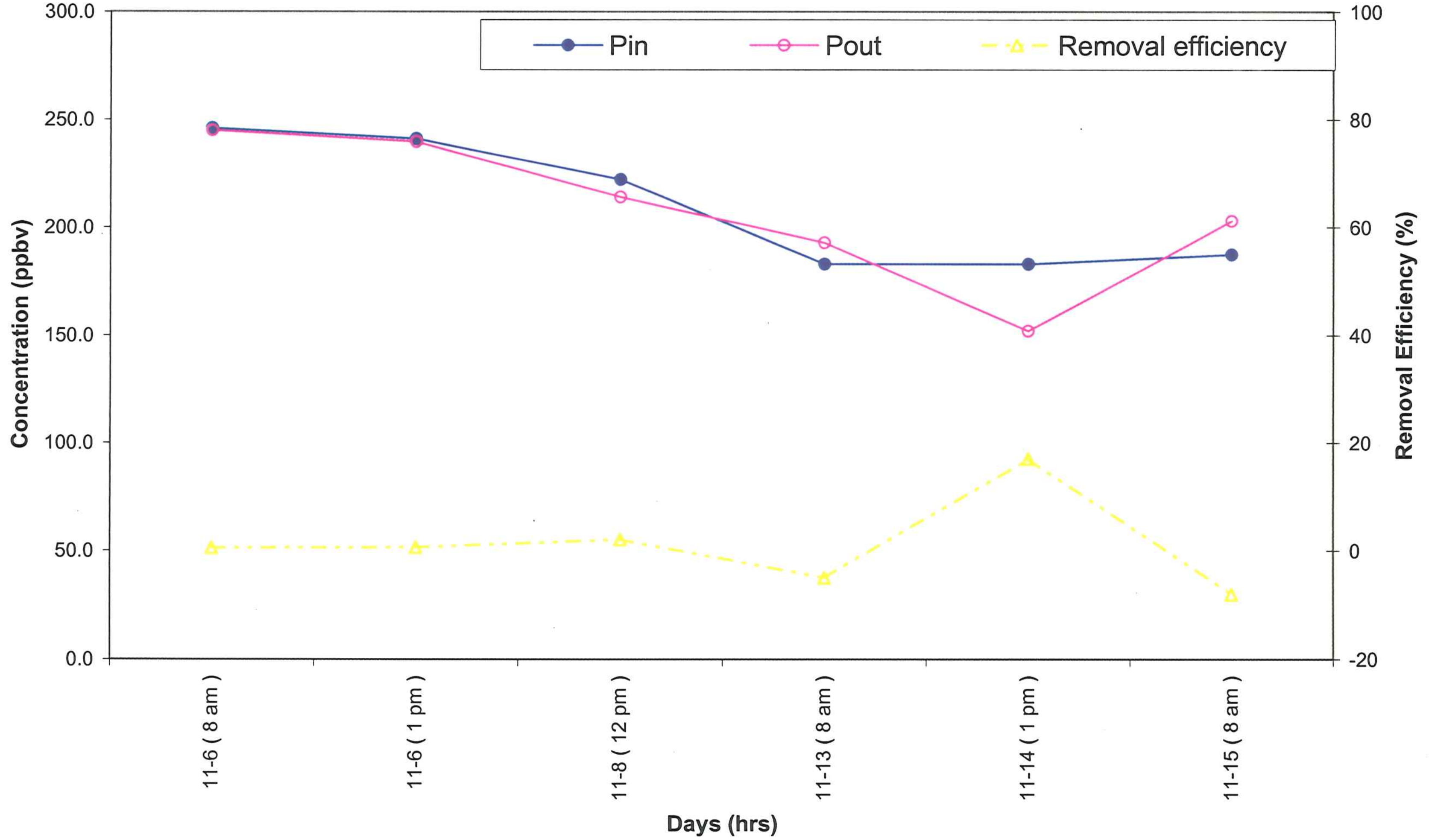


Figure 24. Removal of VOC's in Biotrickling filter - Benzene (Phase II)

Gasoline injection (50μl / second) and
mixture of methylene chloride &TCE injection (25 μl / second)



Figue 25. Removal of VOC's in Biotrickling Filter - Toluene (phase II)

Gasoline injection (50µl / second) and
mixture of methylene chloride &TCE injection (25 µl / second)

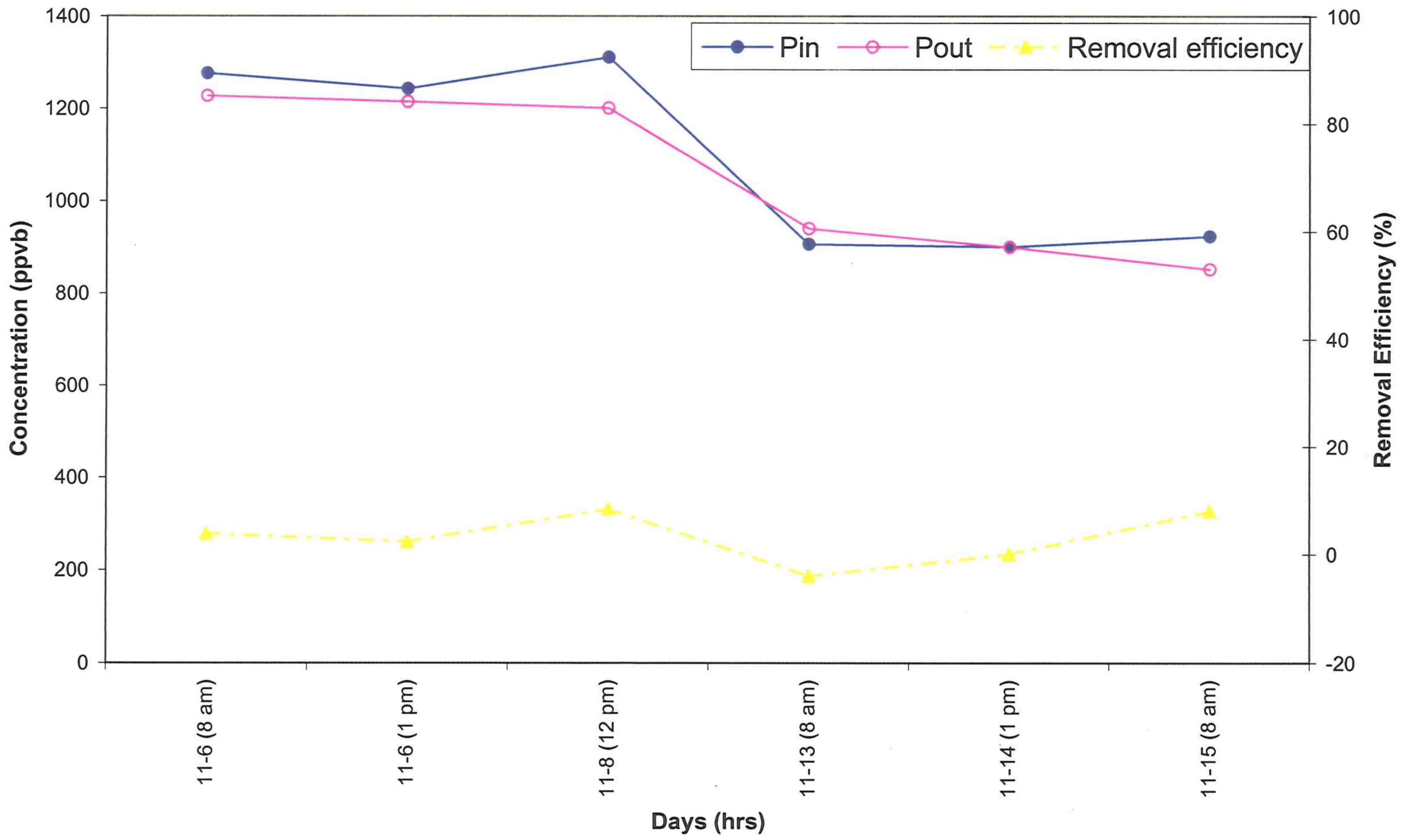


Figure 26. Removal of VOC's in Biotrickling Filter - Total Xylenes (phase II)

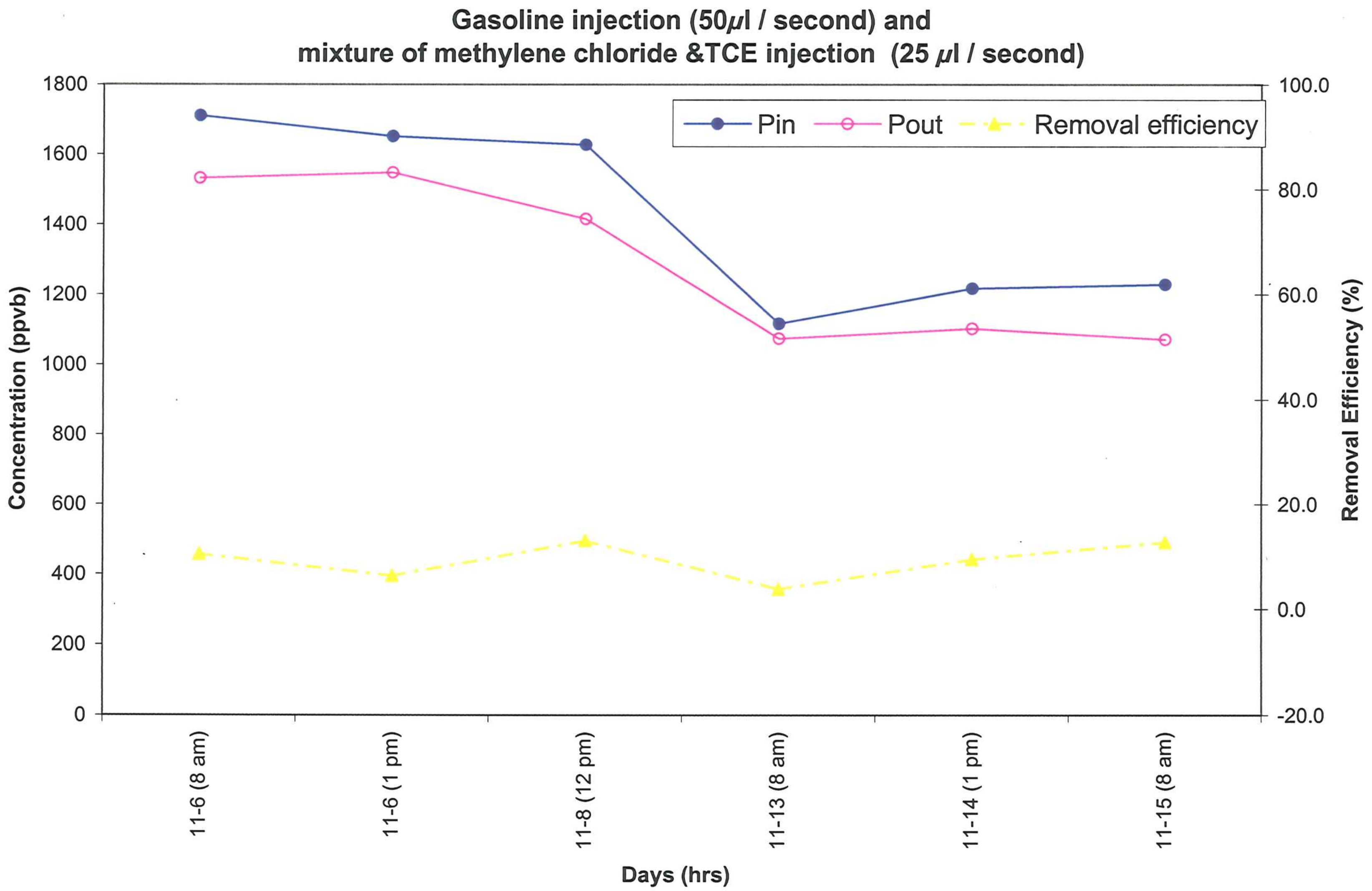
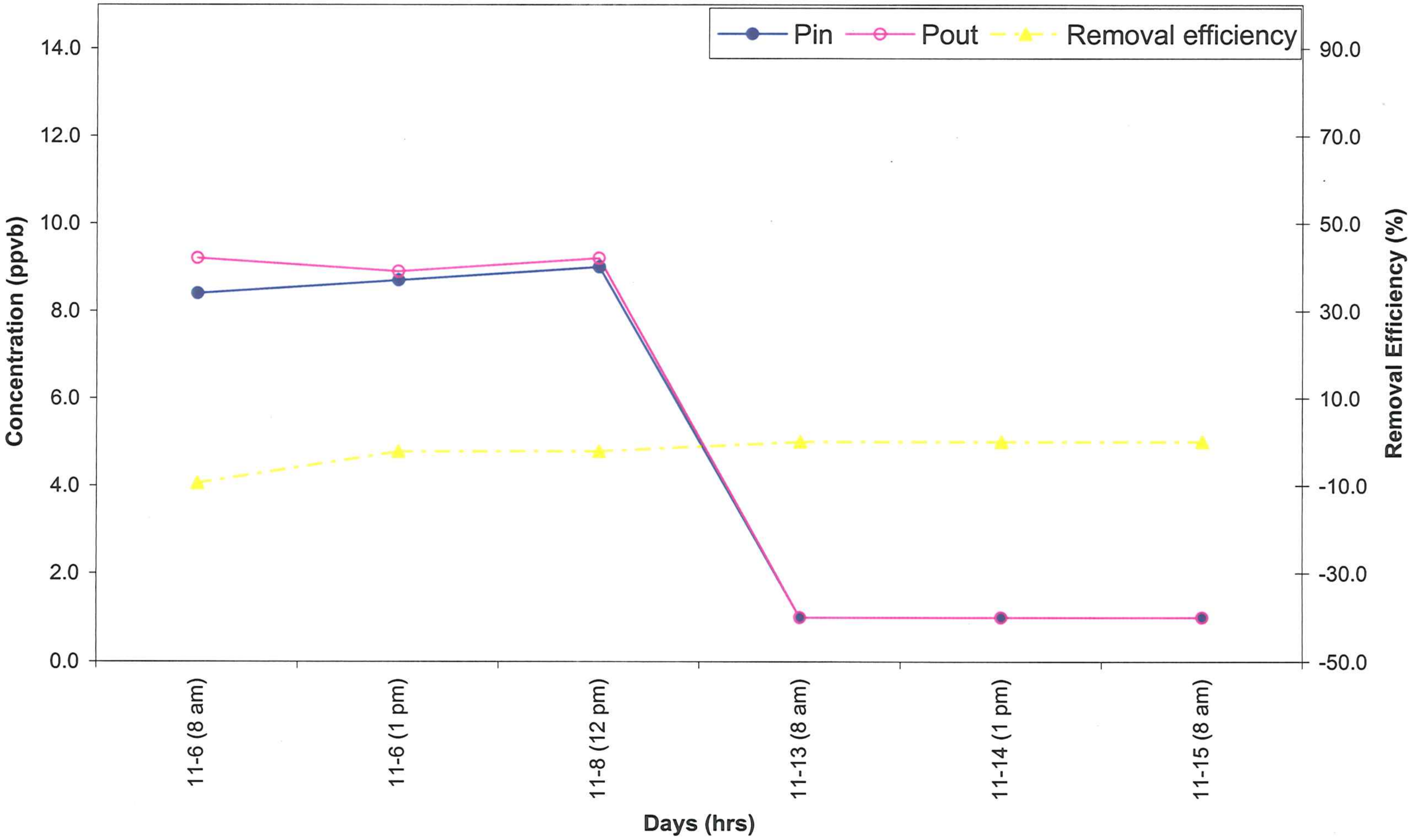


Figure 27. Removal of VOC's in Biotrickling Filter - Dichlorobenzene (phase II)



Gasoline injection (50μl / second) and
mixture of methylene chloride &TCE injection (25 μl / second)

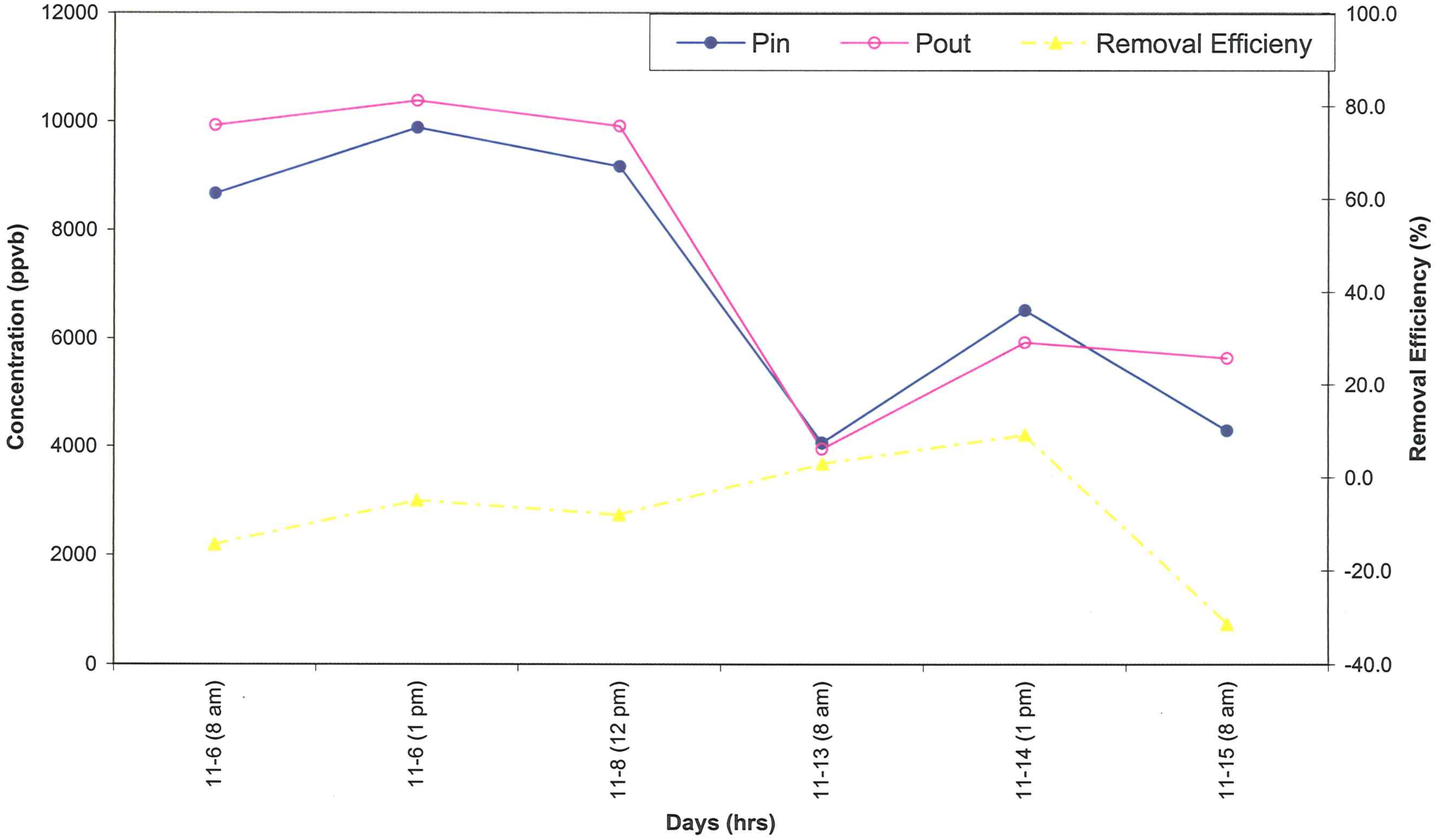


Figure 28. Removal of VOC's in Biotrickling Filter - Methylene Chloride (Phase II)

Gasoline injection (50μl / second) and
mixture of methylene chloride &TCE injection (25 μl / second)

Figure 29. Removal of VOC's in Biotrickling Filter - Chloroform (Phase II)

Gasoline injection rate (50μl / second) and
mixture of methylene chloride &TCE injection rate (25 μl / second)

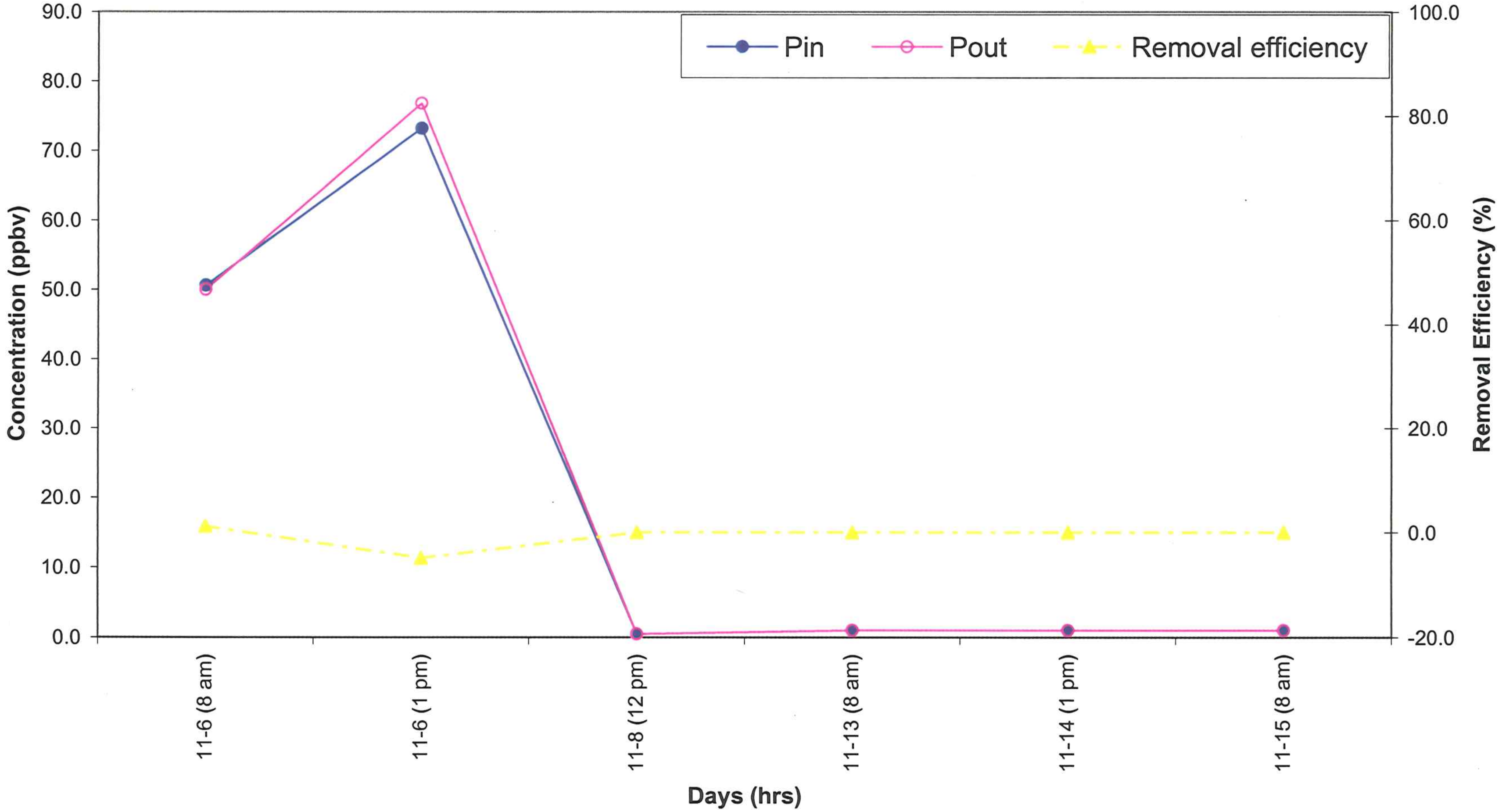
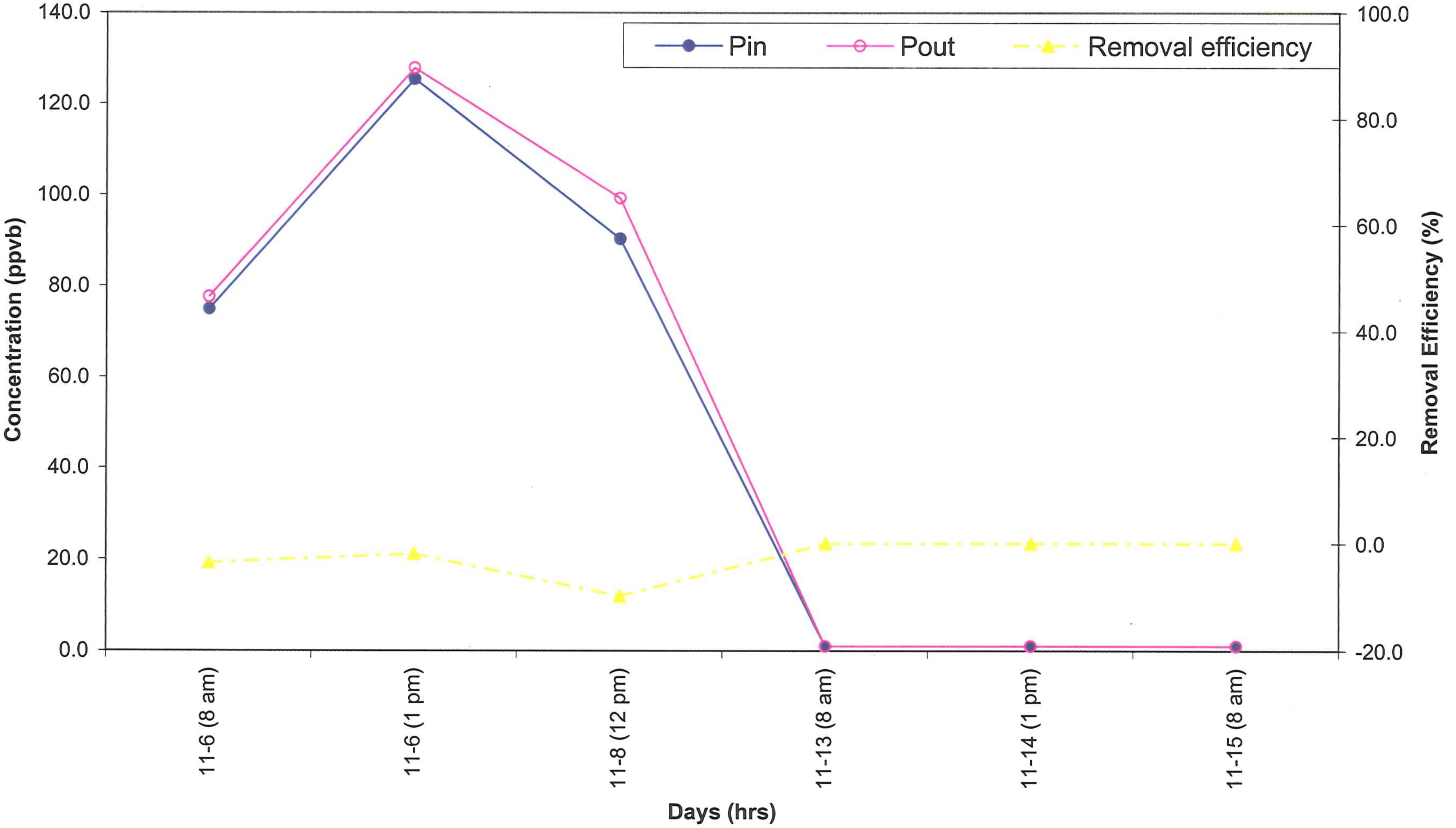


Figure 30. Removal of VOC's in Biotrickling Filter - Tetrachloroethylene (Phase II)

Gasoline injection (50μl / second) and
mixture of methylene chloride &TCE injection (25 μl / second)



PHASE III

VOCs FIGURES

Figure 31. Removal of VOCs in Biofilter, Benzene (phase III)

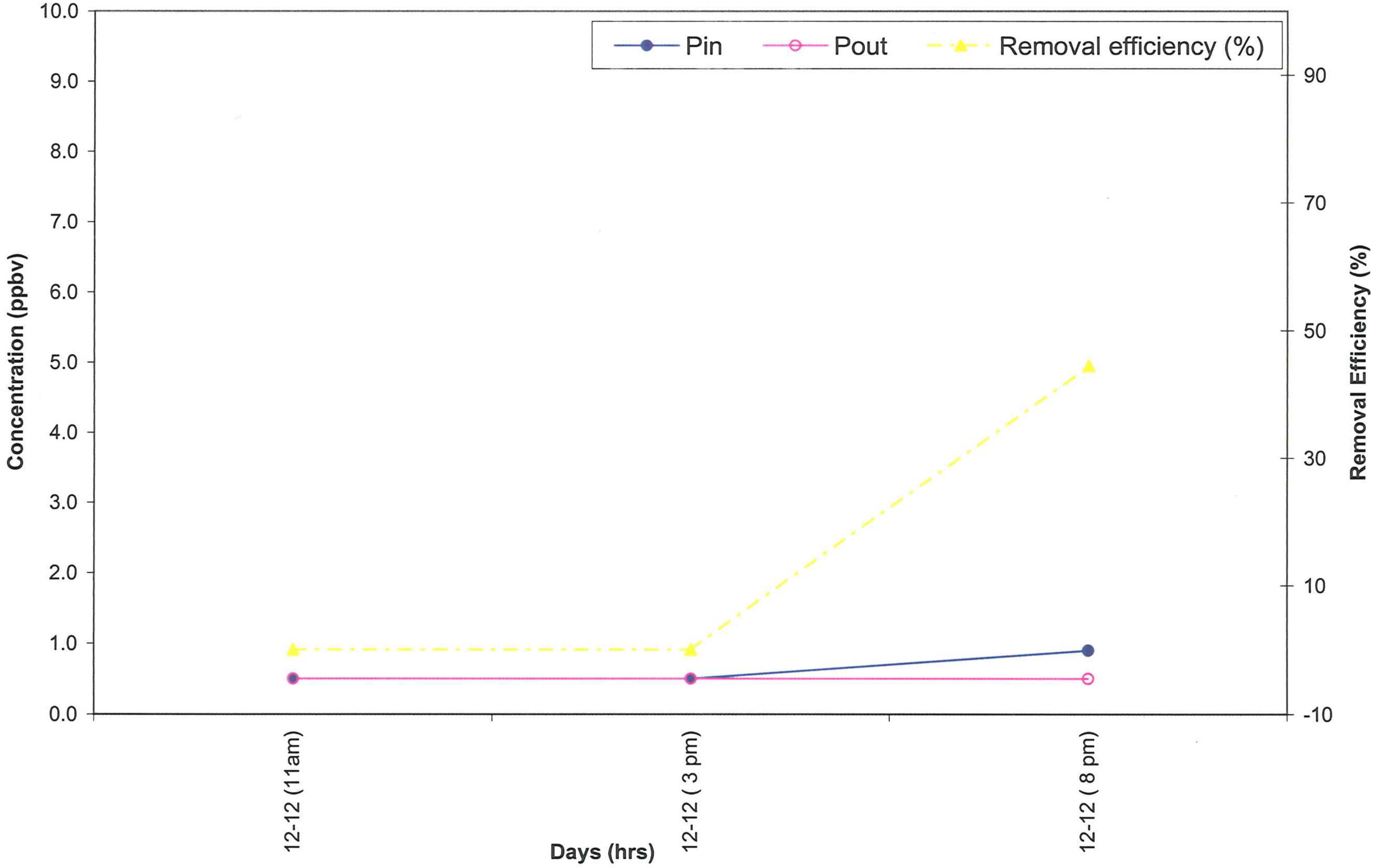


Figure 32. Removal of VOCs in Biofilter, Toluene (Phase III)

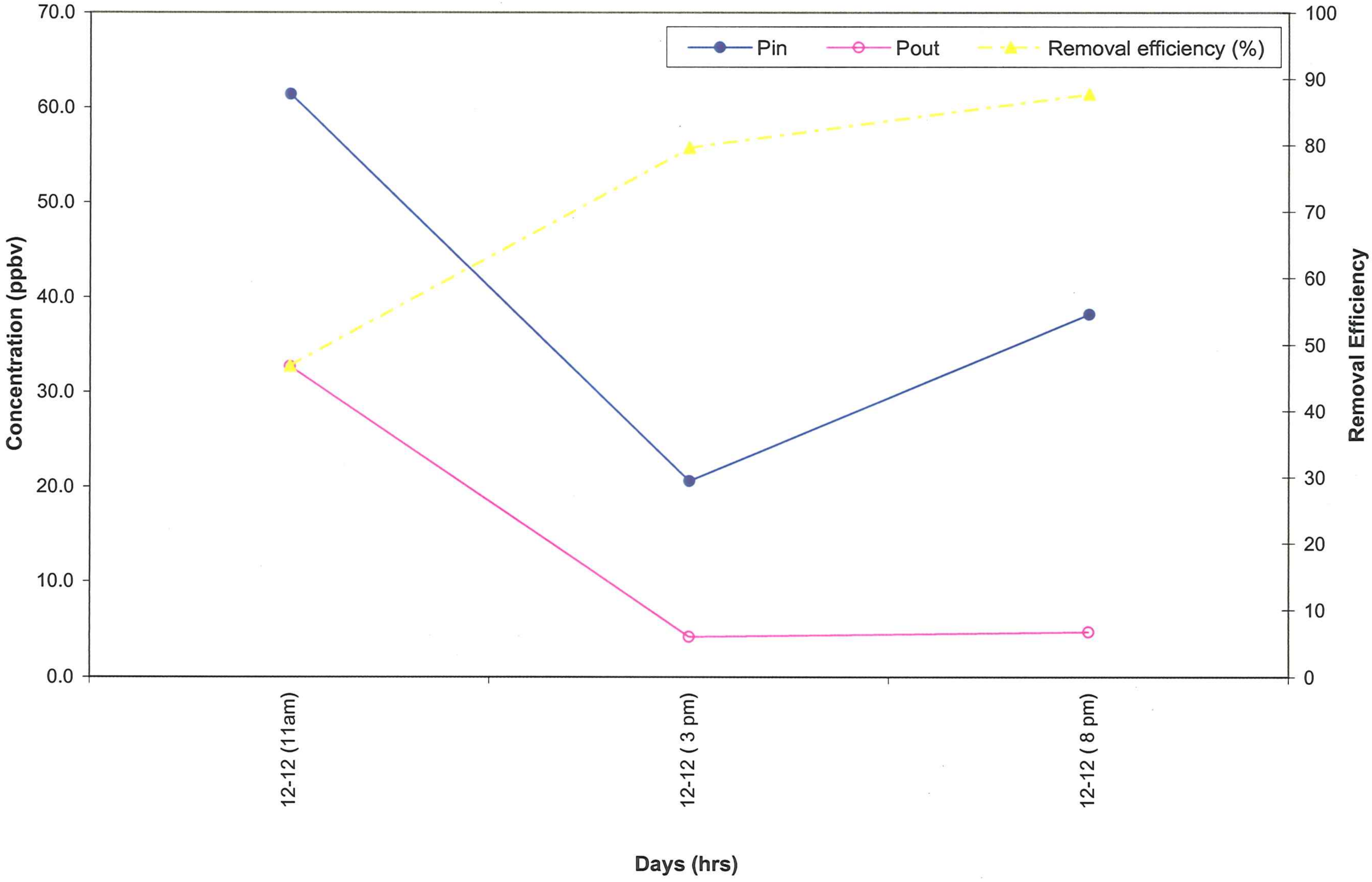


Figure 33. Removal of VOCs in Biofilter, Total Xylenes (Phase III)

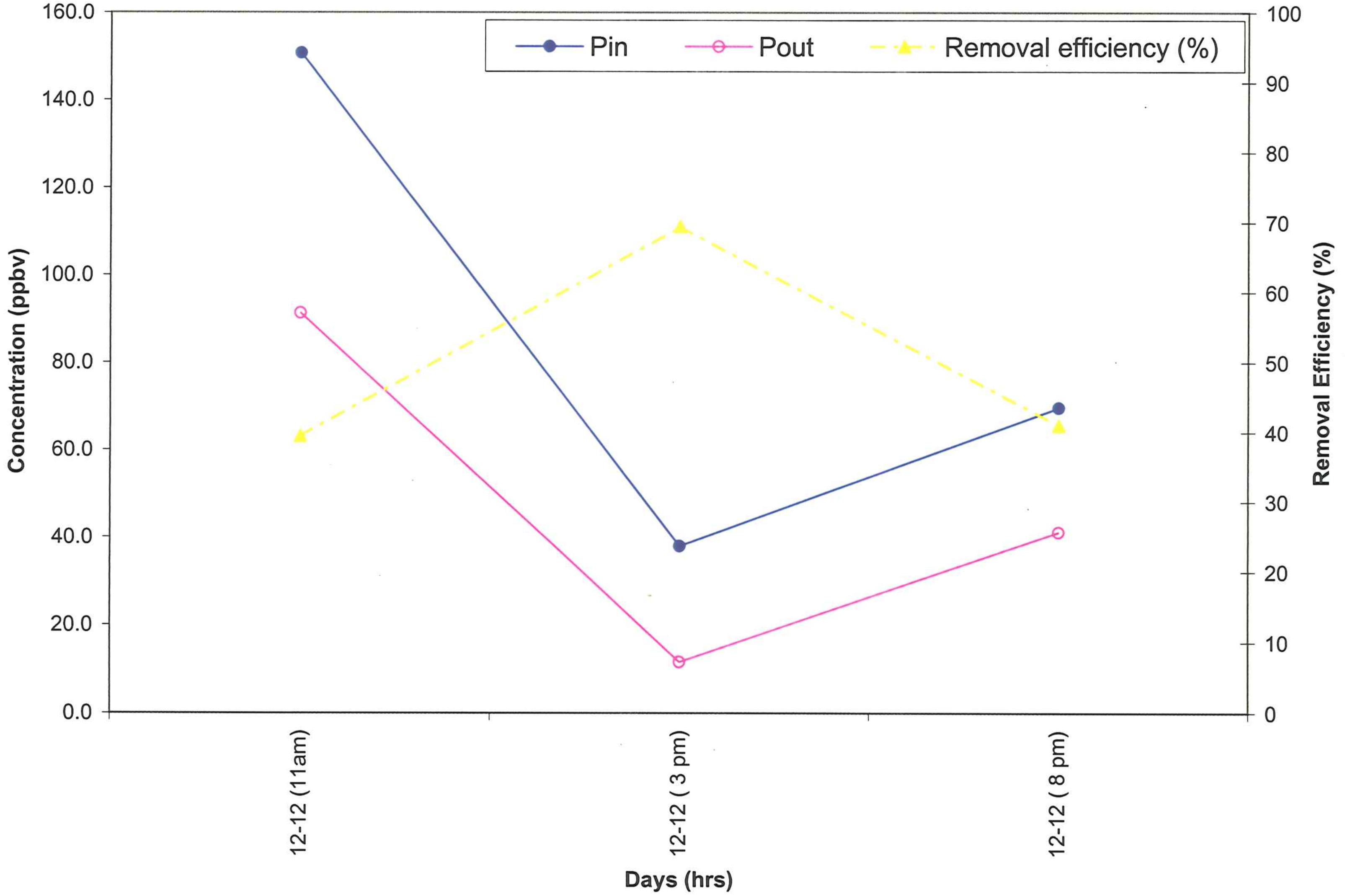


Figure 34. Removal of VOCs in Biofilter, Dichlorobenzene (Phase III)

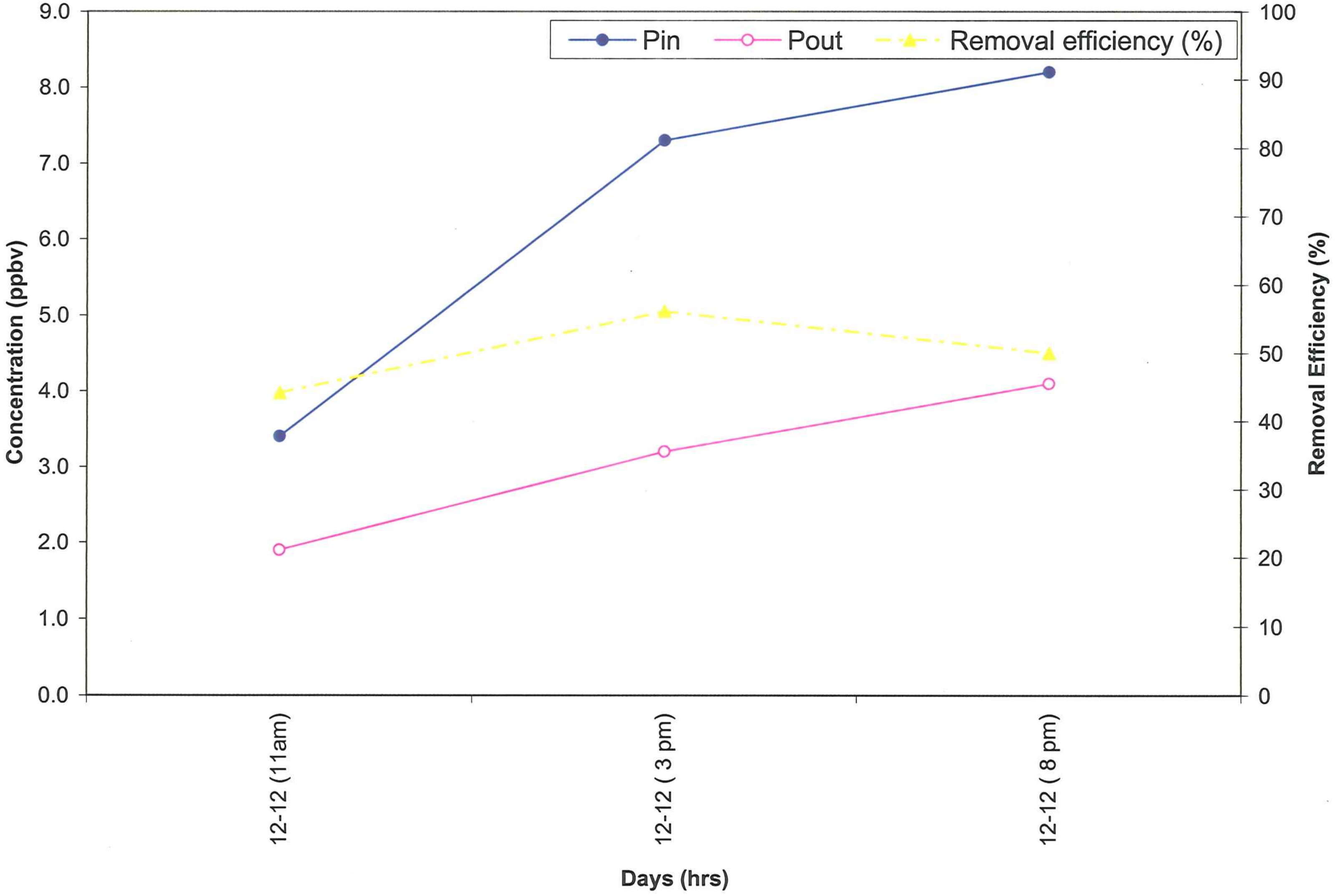


Figure 35. Removal of VOCs in Biofilter, Methylene Chloride (phase III)

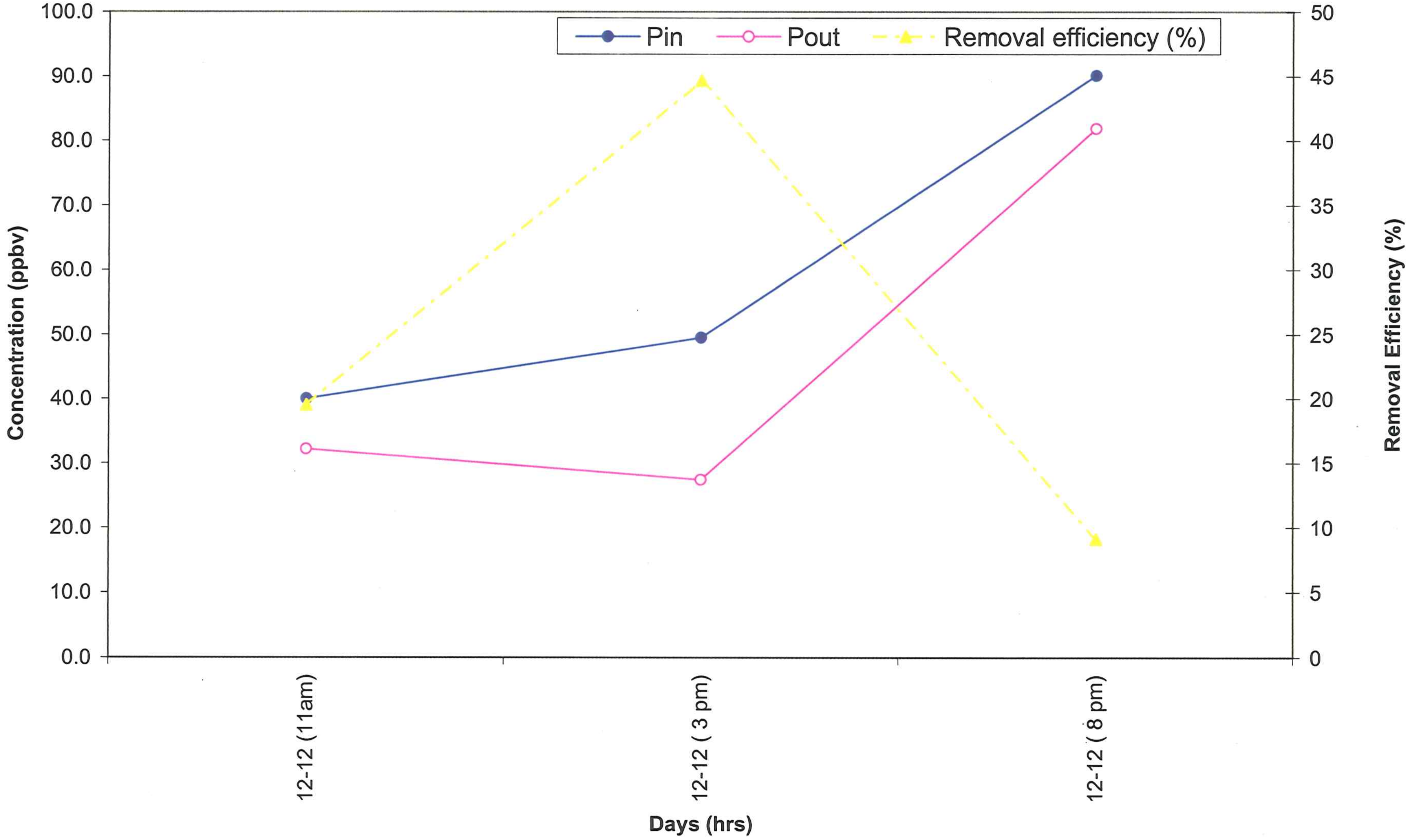


Figure 36. Removal of VOCs in Biofilter, Chloroform (phase III)

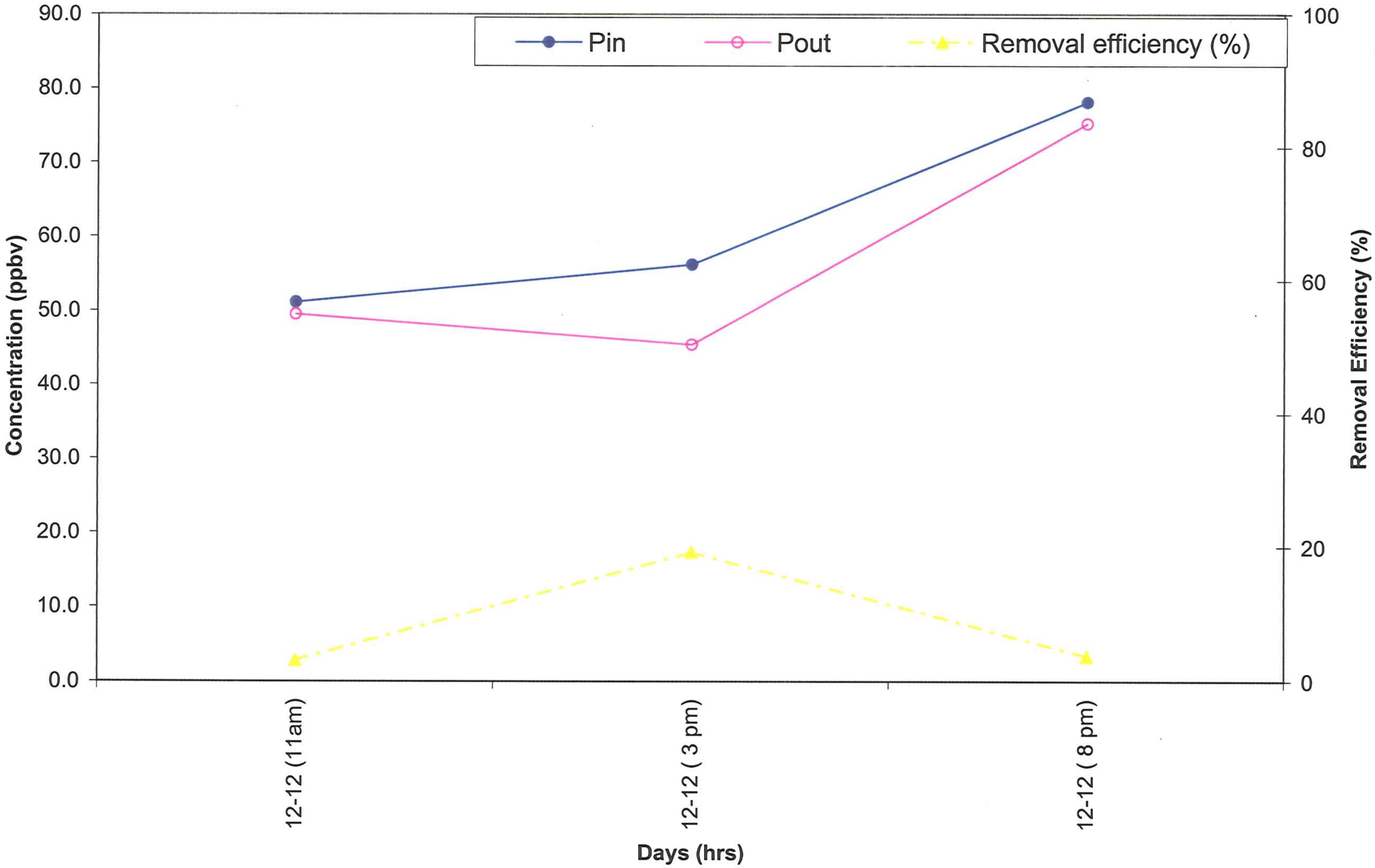


Figure 37. Removal of VOCs in Biofilter, Tetrachloroethylene (phase III)

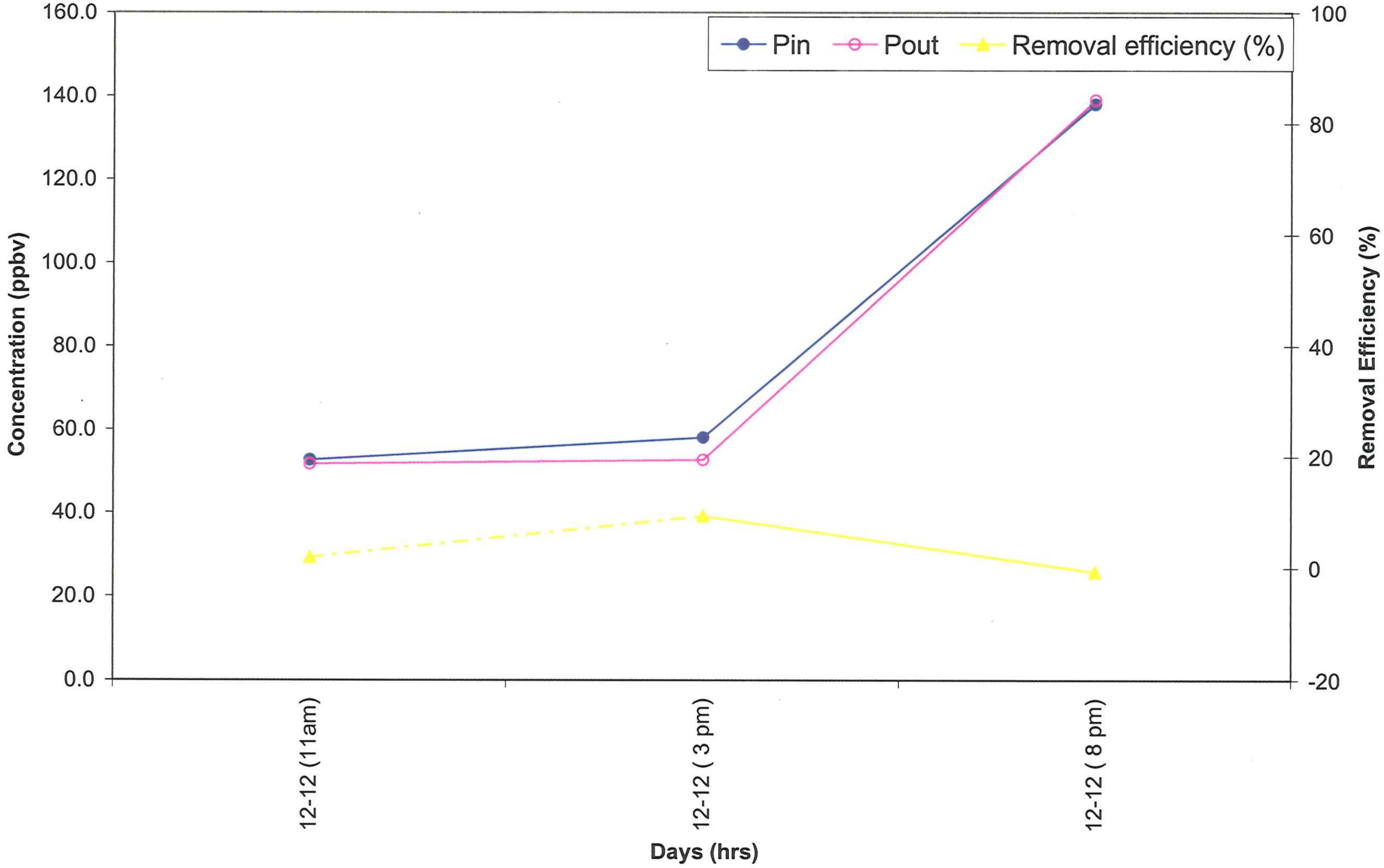


Figure 38. Removal of VOCs in Biotrickling Filter, Benzene (phase III)

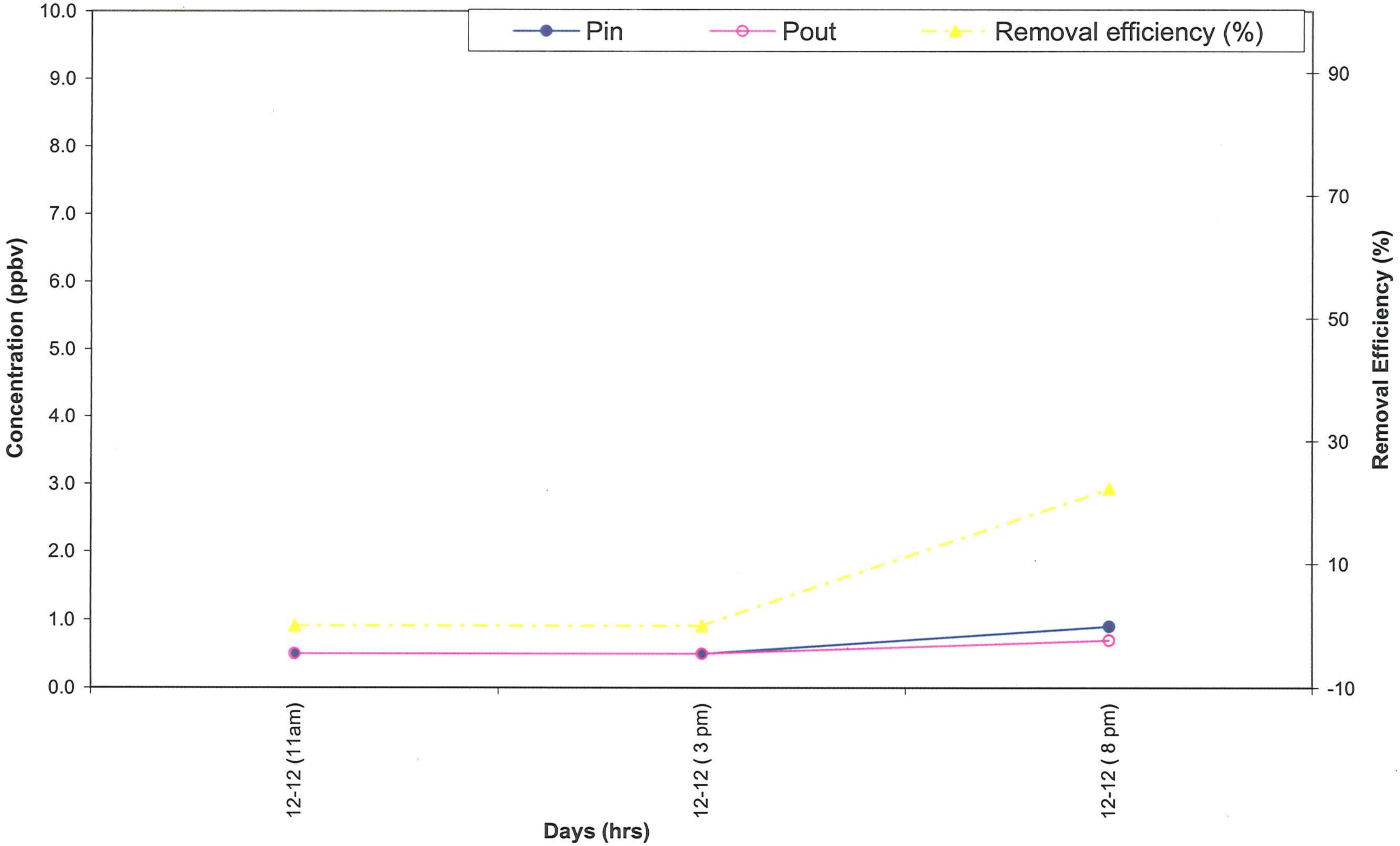


Figure 39. Removal of VOCs in Biotrickling Filter, Toluene (phase III)

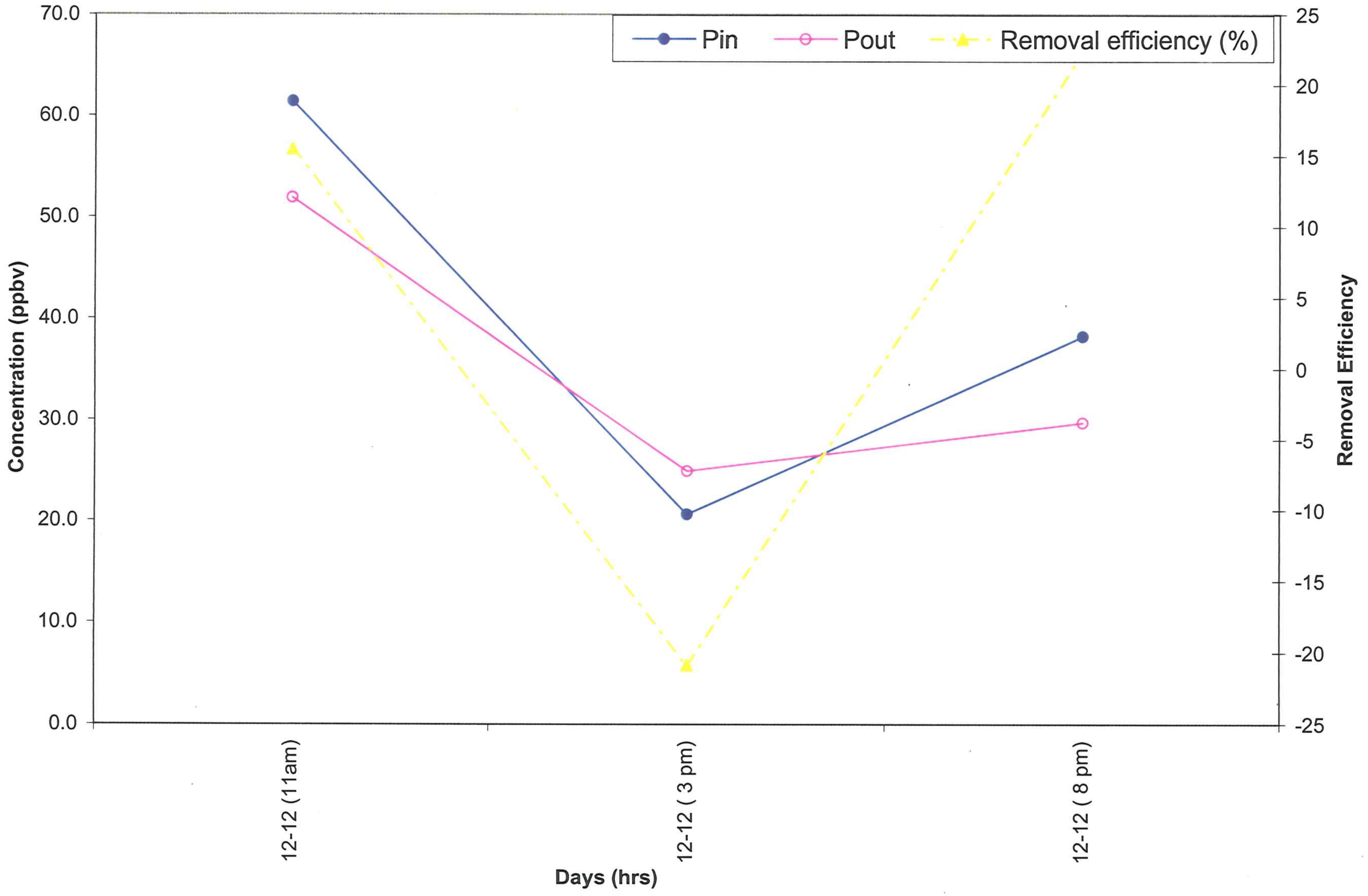


Figure 40. Removal of VOCs in Biotrickling Filter, Total Xylenes (phase III)

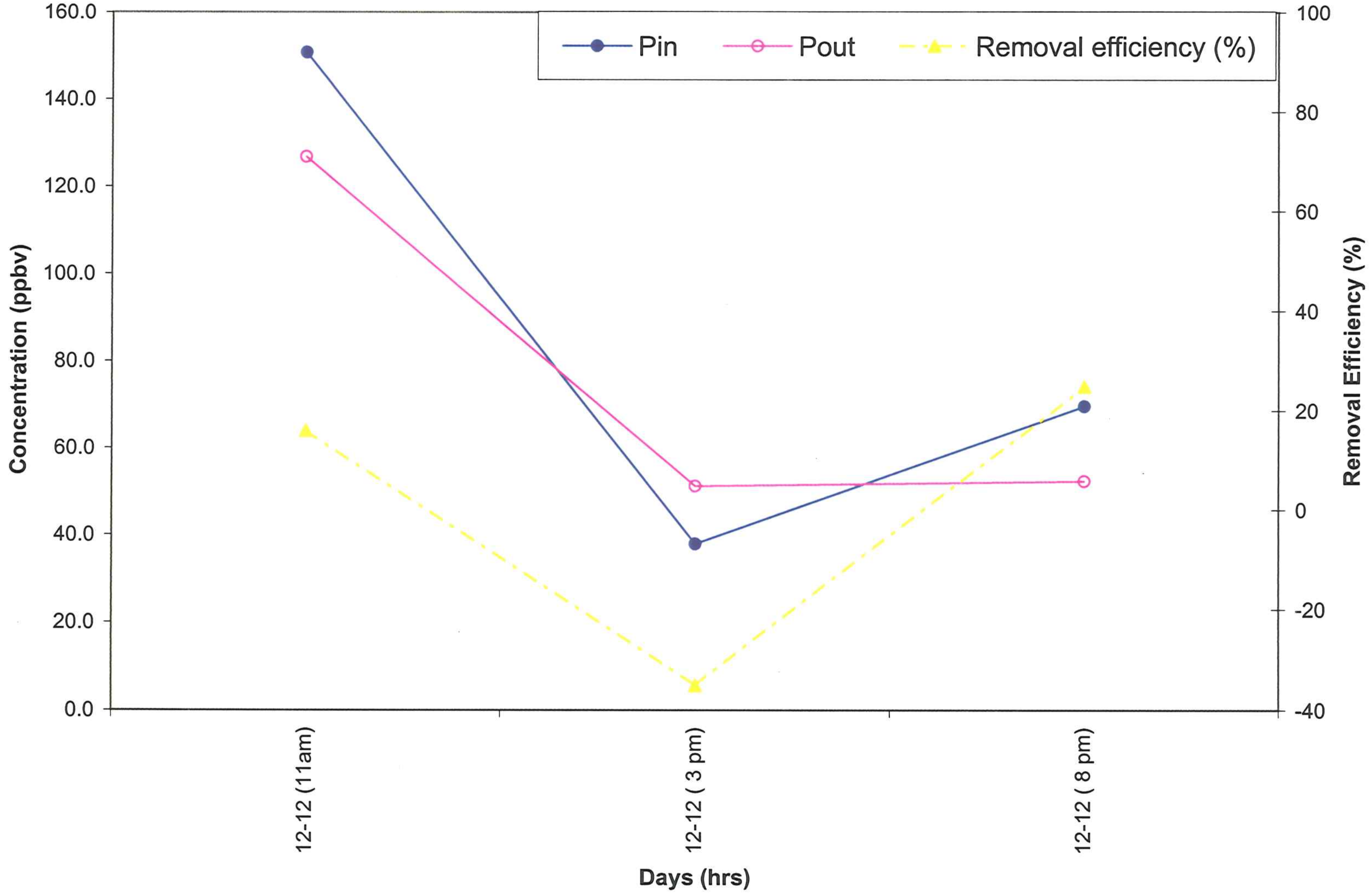


Figure 41. Removal of VOCs in Biotrickling Filter,Dichlorobenzene (phase III)

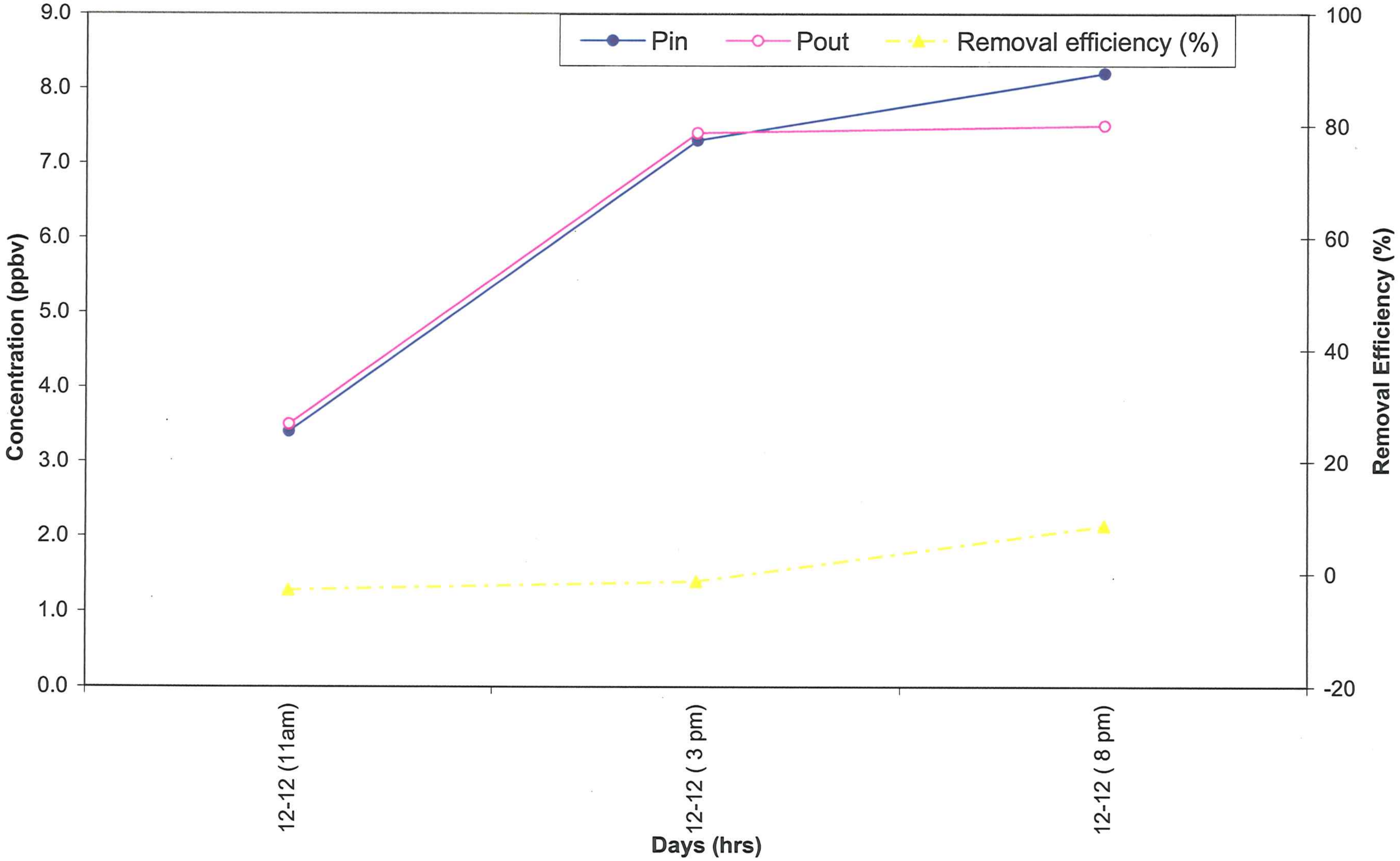


Figure 42. Removal of VOCs in Biotrickling Filter, Methylene Chloride (Phase III)

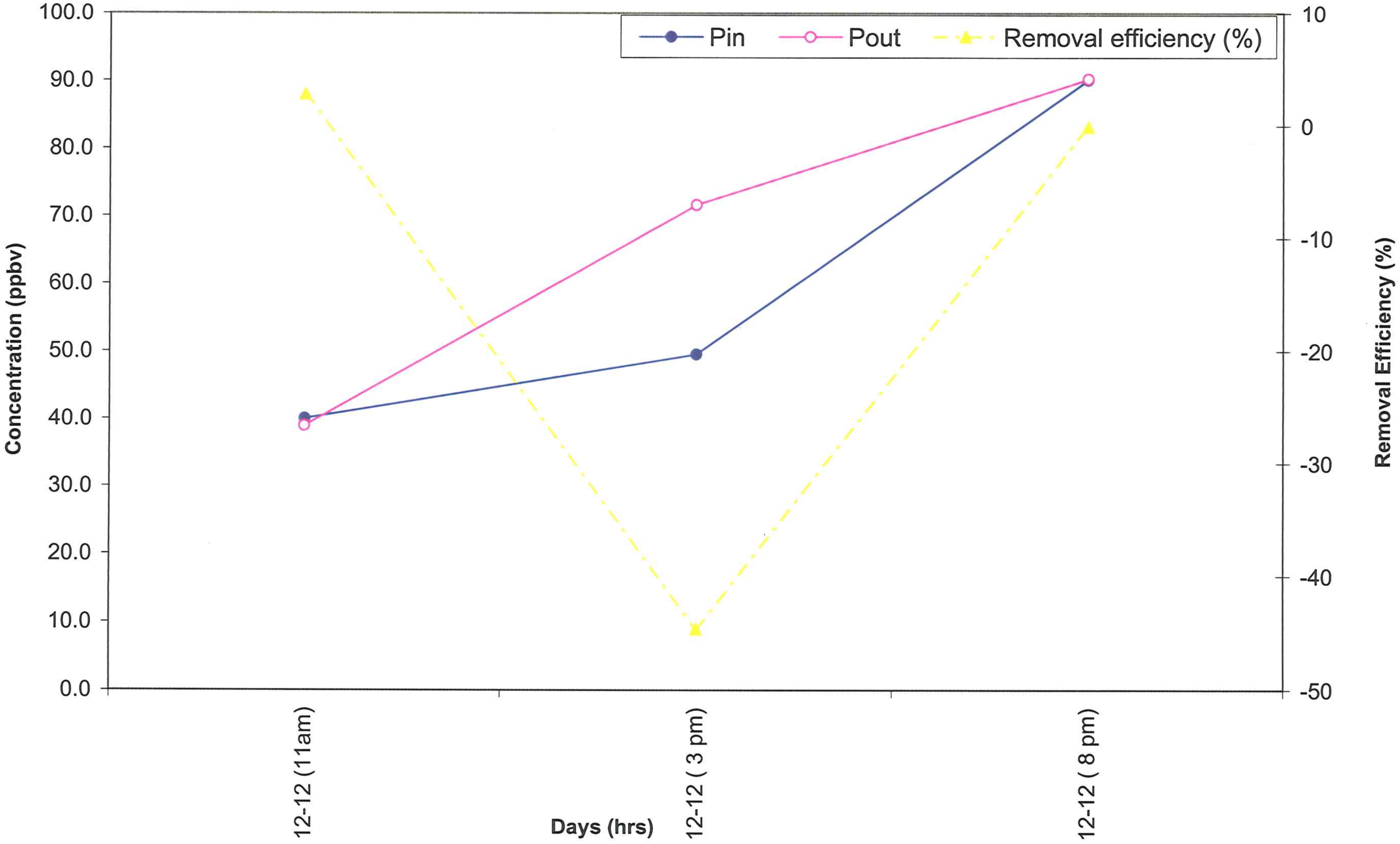


Figure 43. Removal of VOCs in Biotrickling Filter, Chloroform (Phase III)

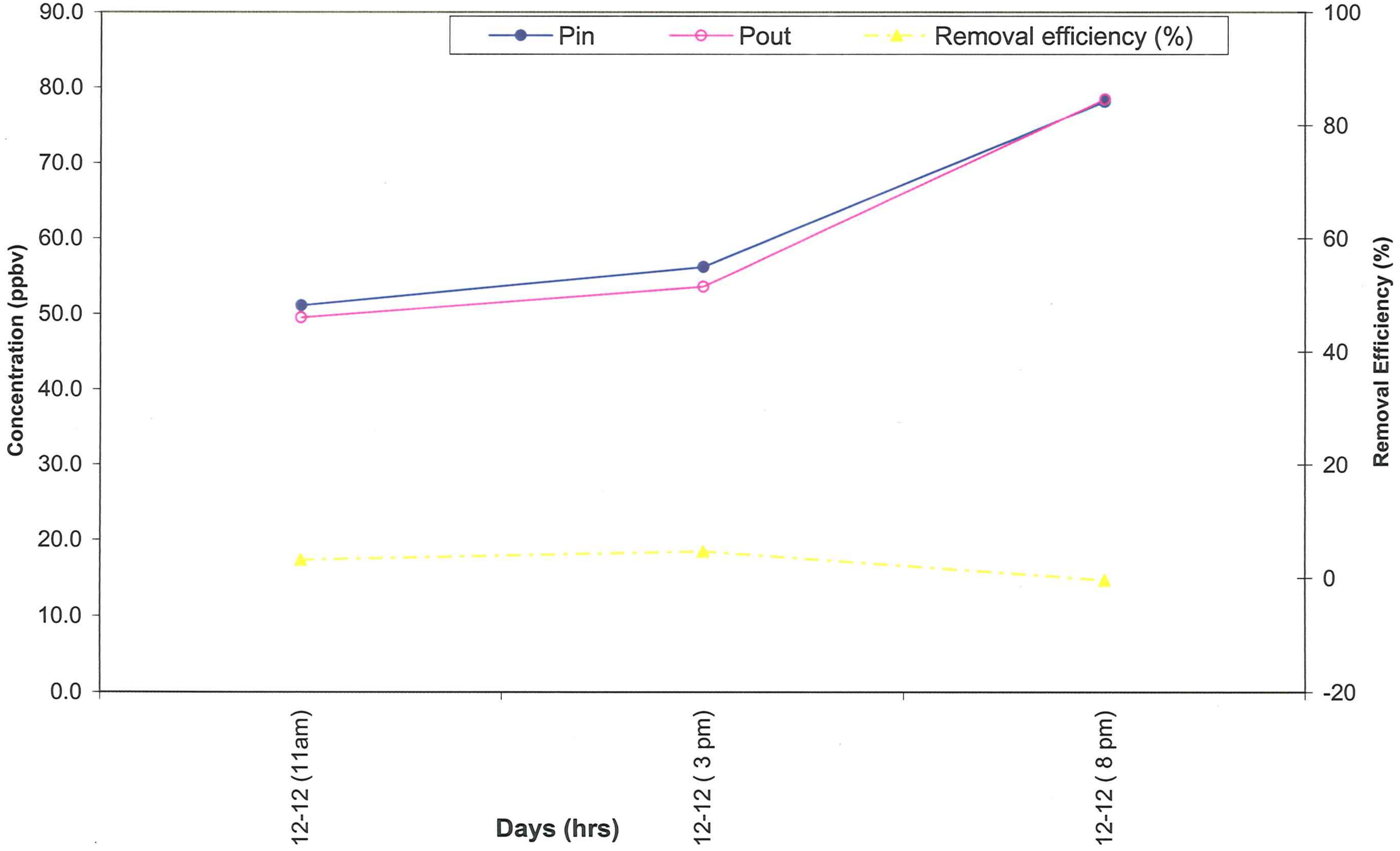


Figure 44. Removal of VOCs in Biotrickling Filter, Tetrachloroethylene (Phase III)

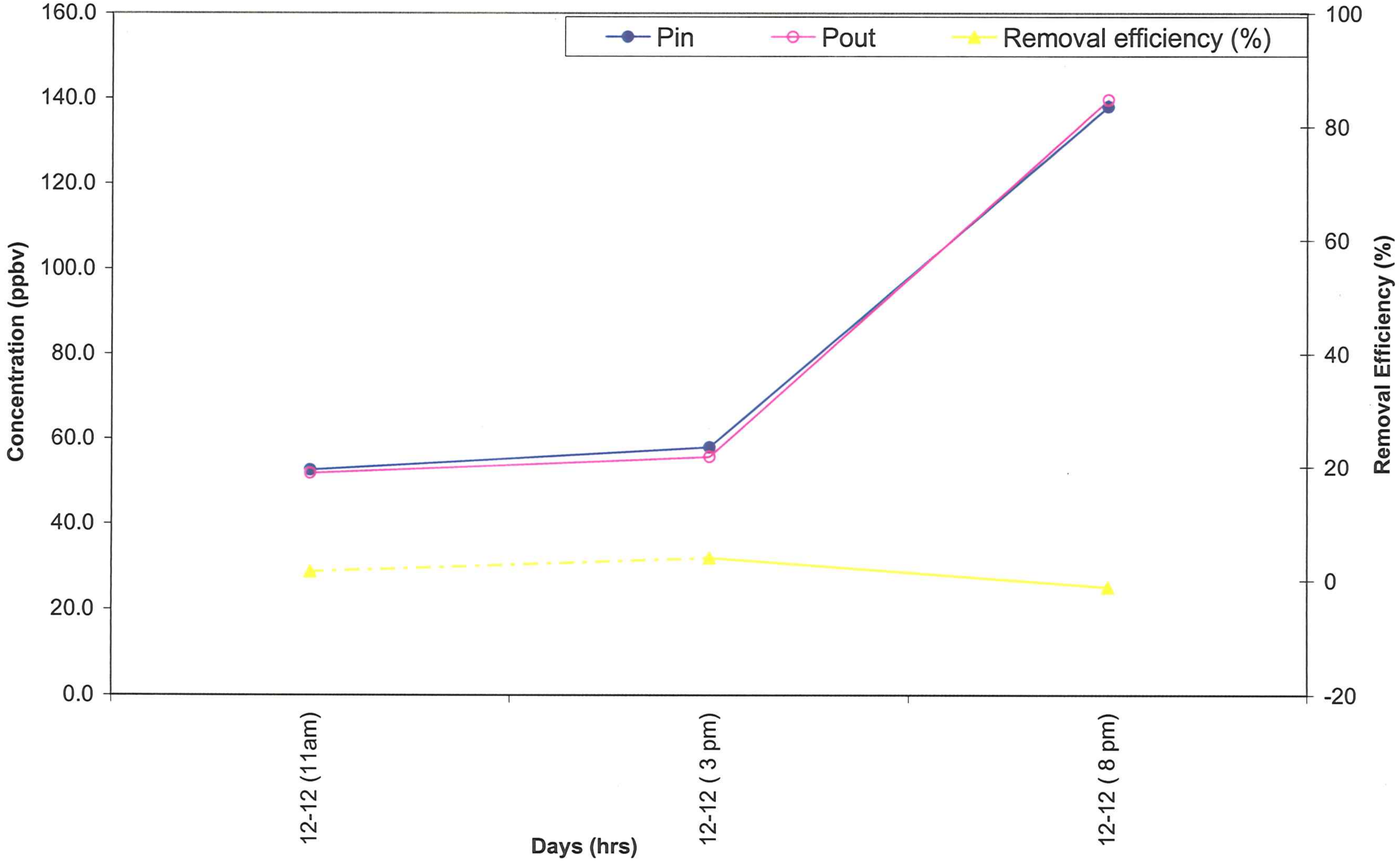


Figure 45. Odor Removal in Biofilter

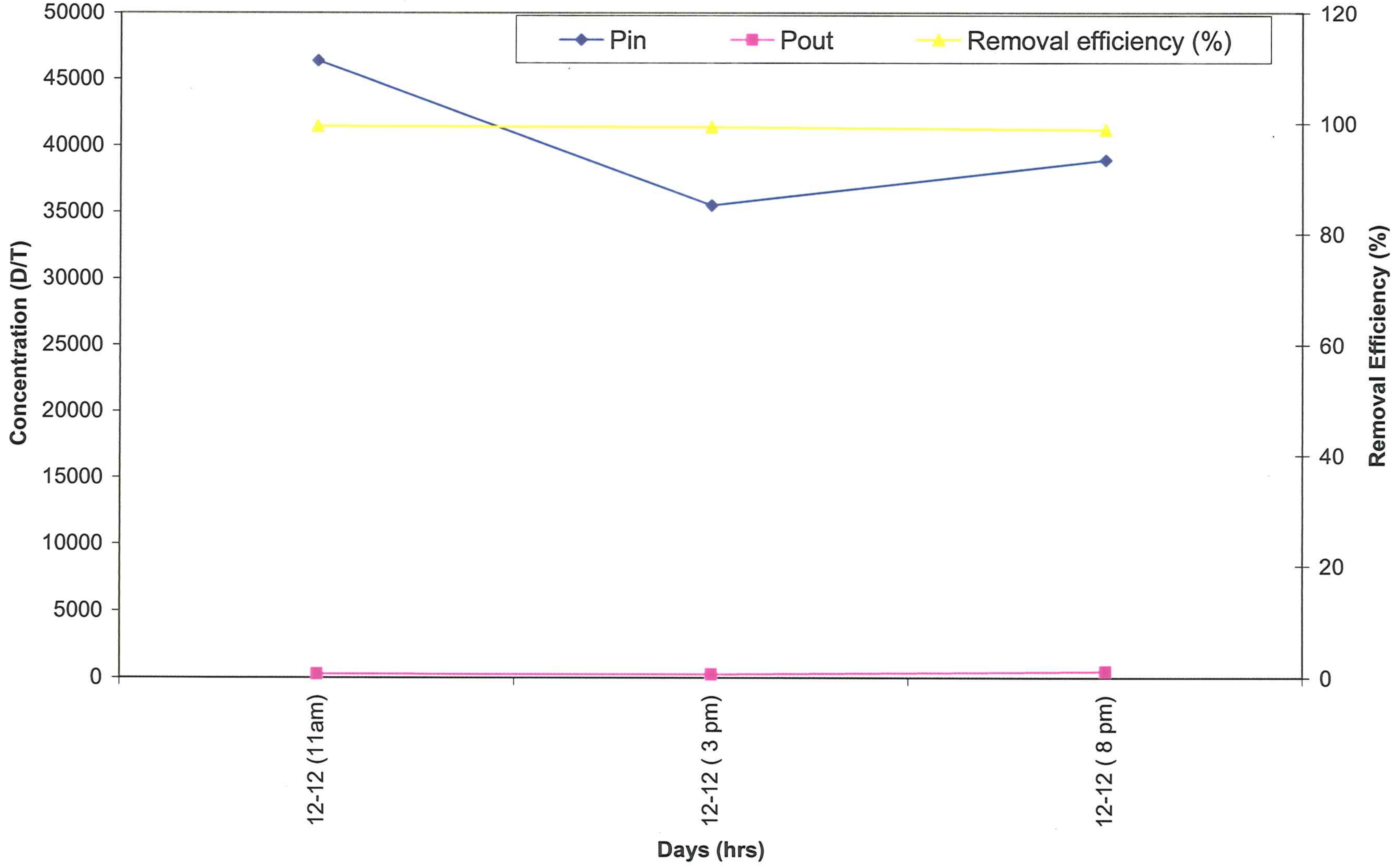


Figure 46. Removal of Hydrogen Sulfide in Biofilter

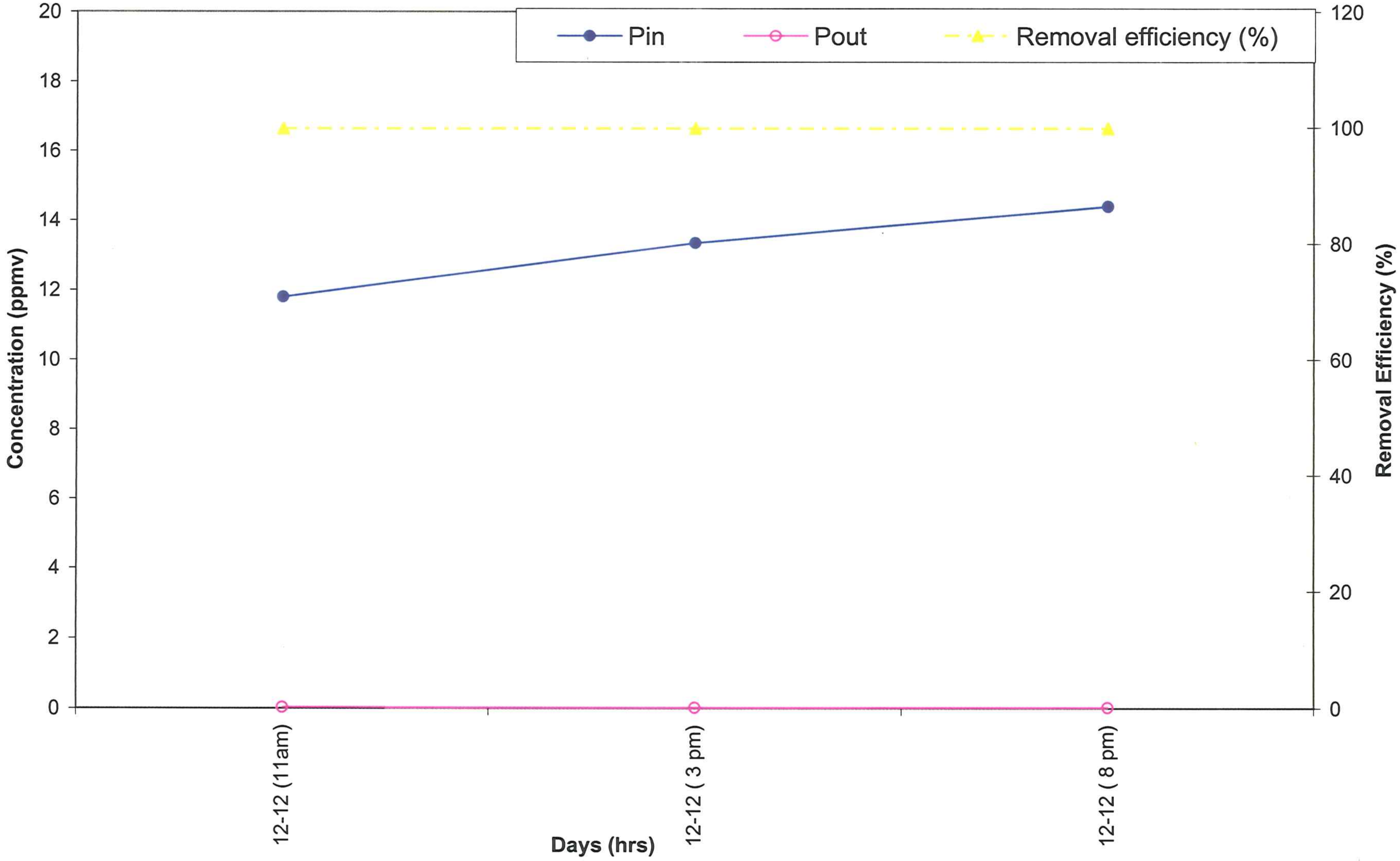


Figure 47. Removal of Carbonyl Sulfide in Biofilter

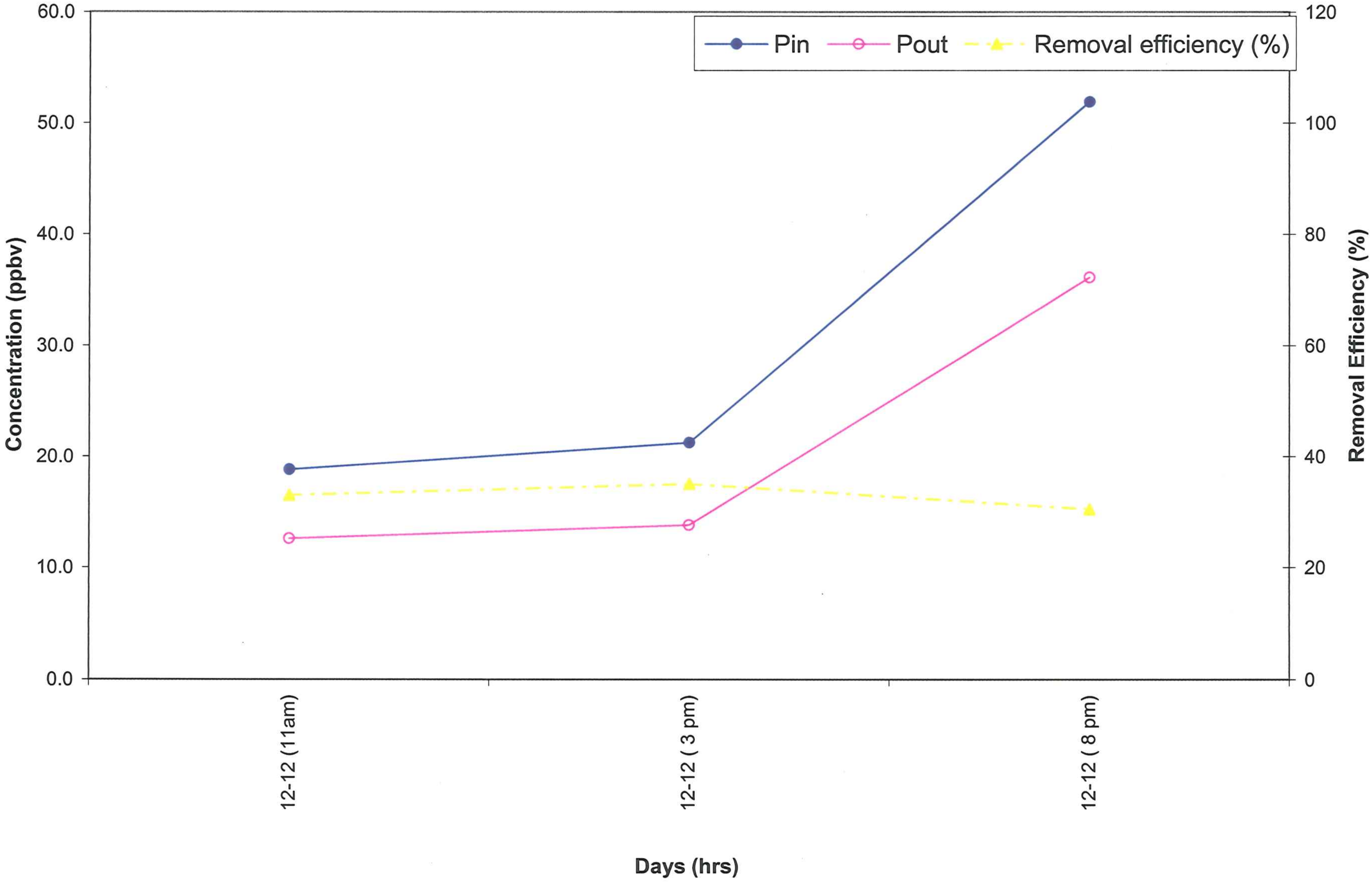


Figure 48. Removal of Methyl Mercaptan in Biofilter

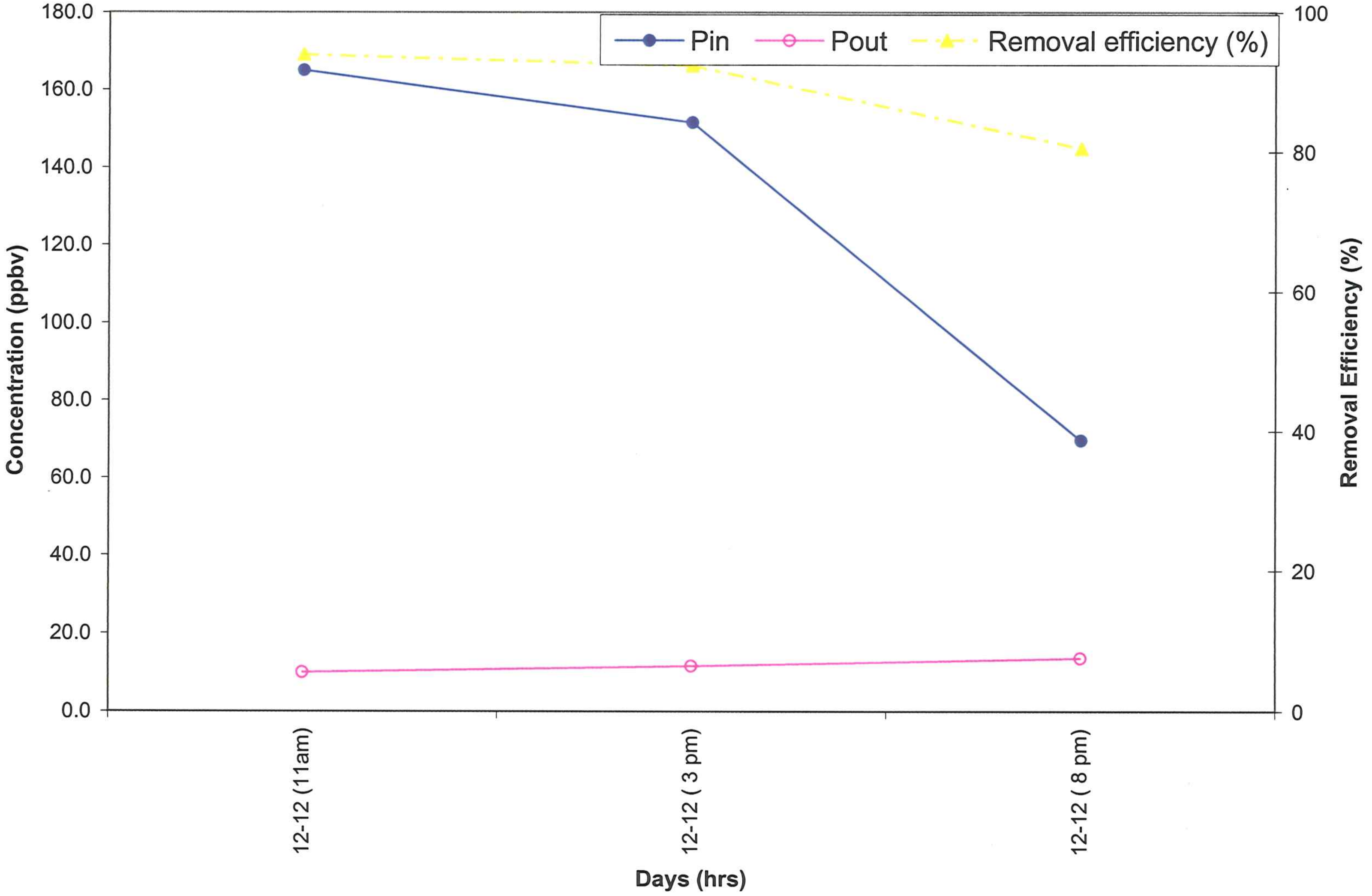


Figure 49. Removal of Dimethyle Sulfide in Biofilter

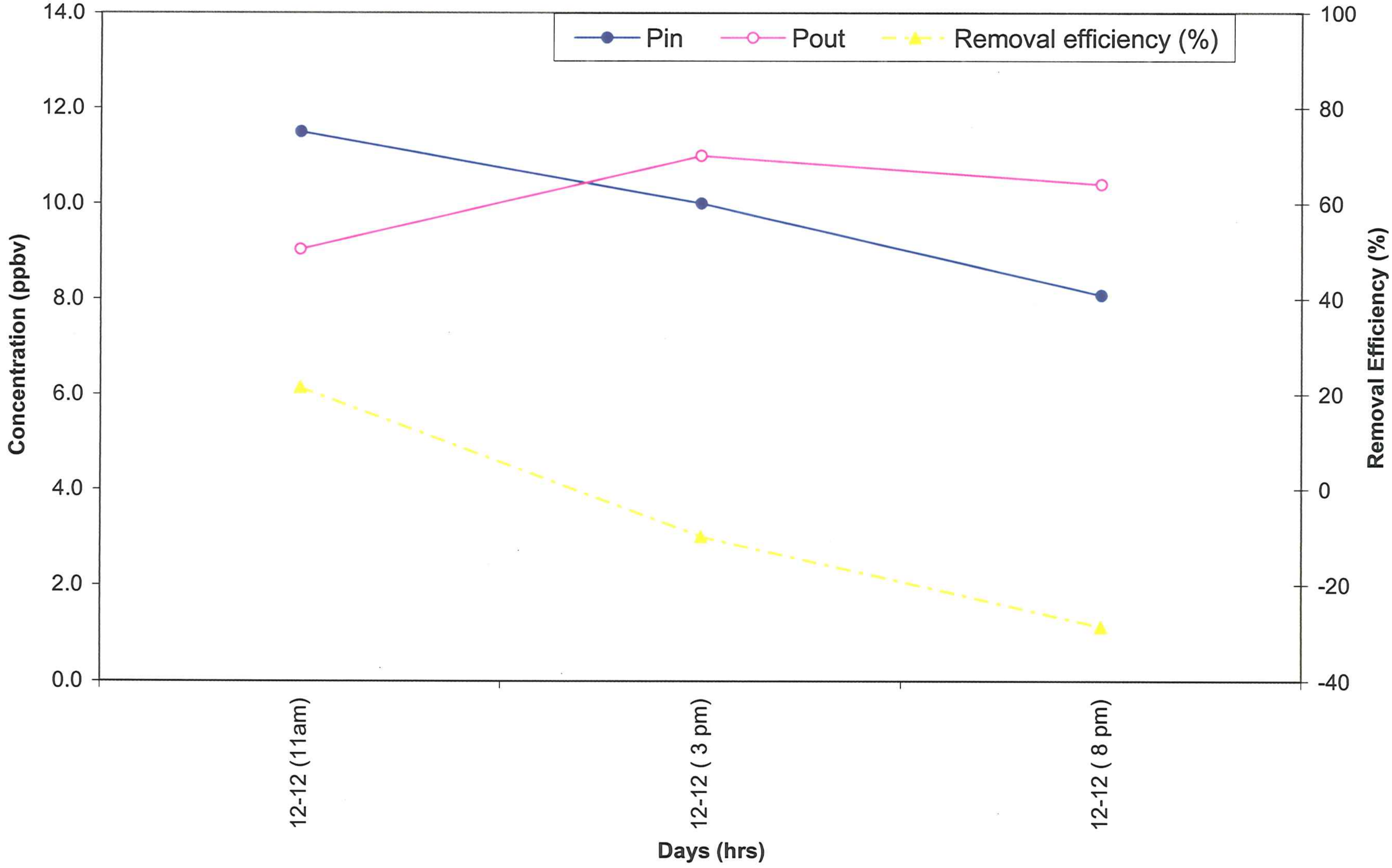
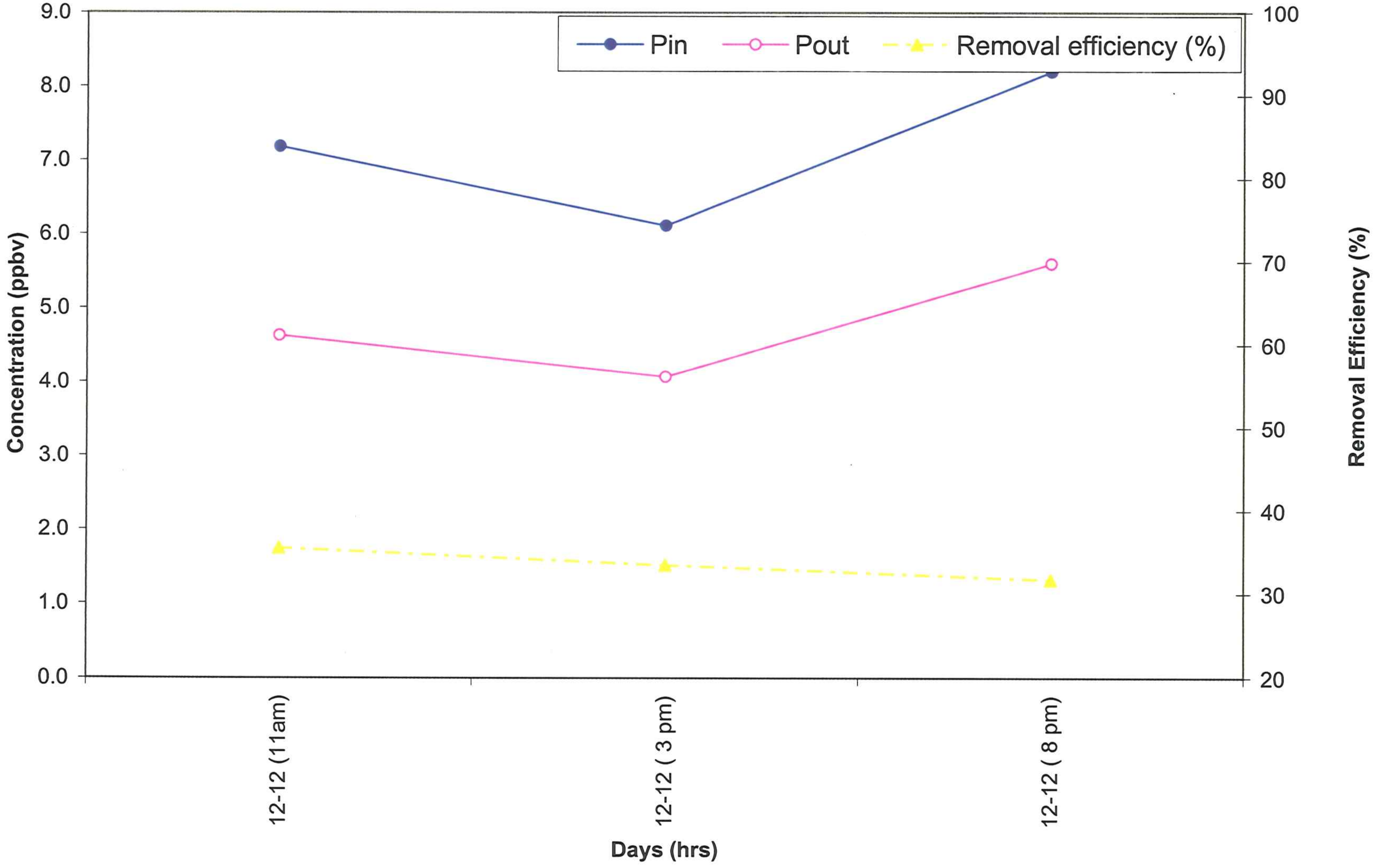


Figure 50. Removal of Carbon Disulfide in Biofilter



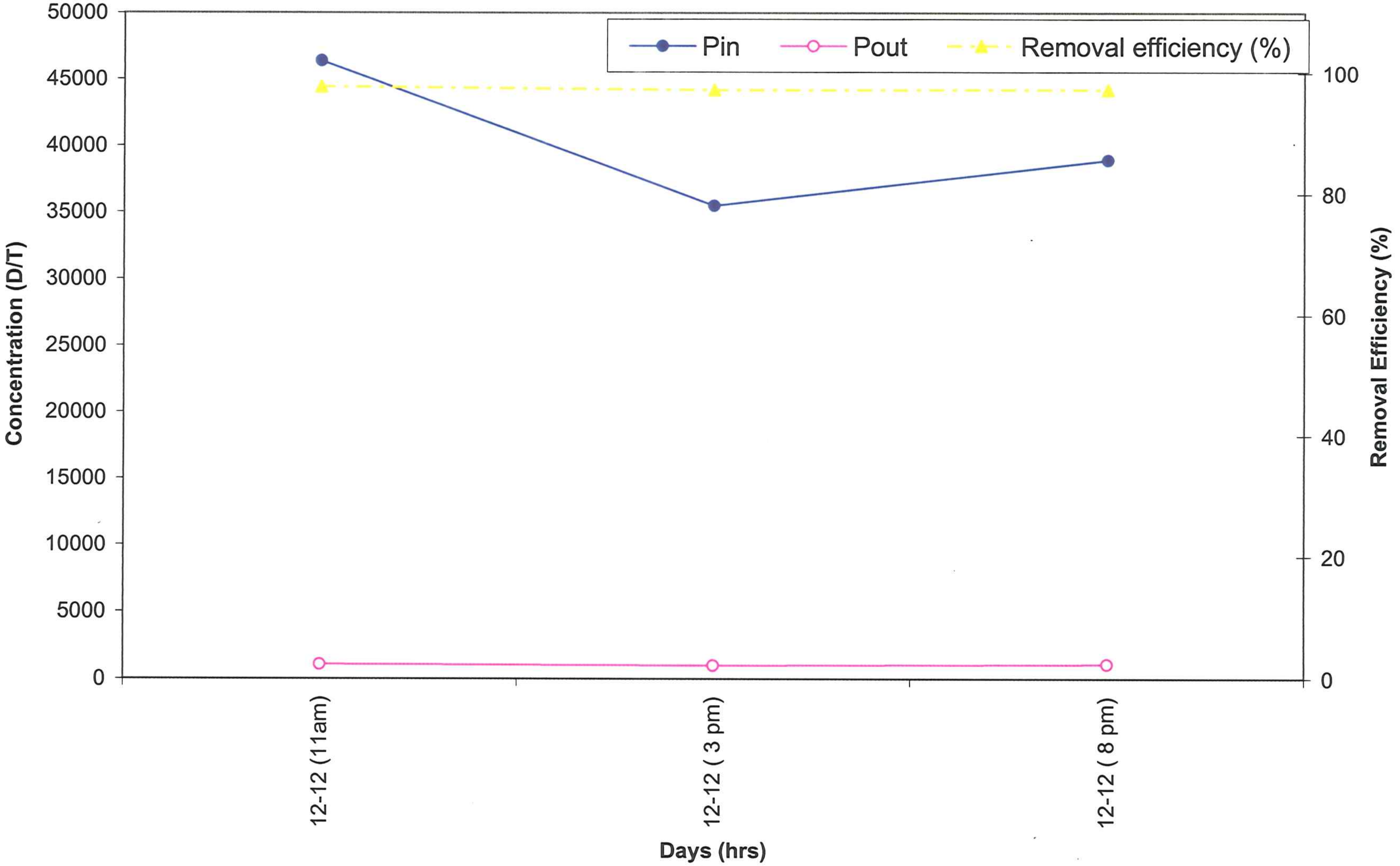


Figure 51. Odor Removal in Biotrickling Filter

Figure 52. Removal of Hydrogen Sulfide in Biotrickling Filter

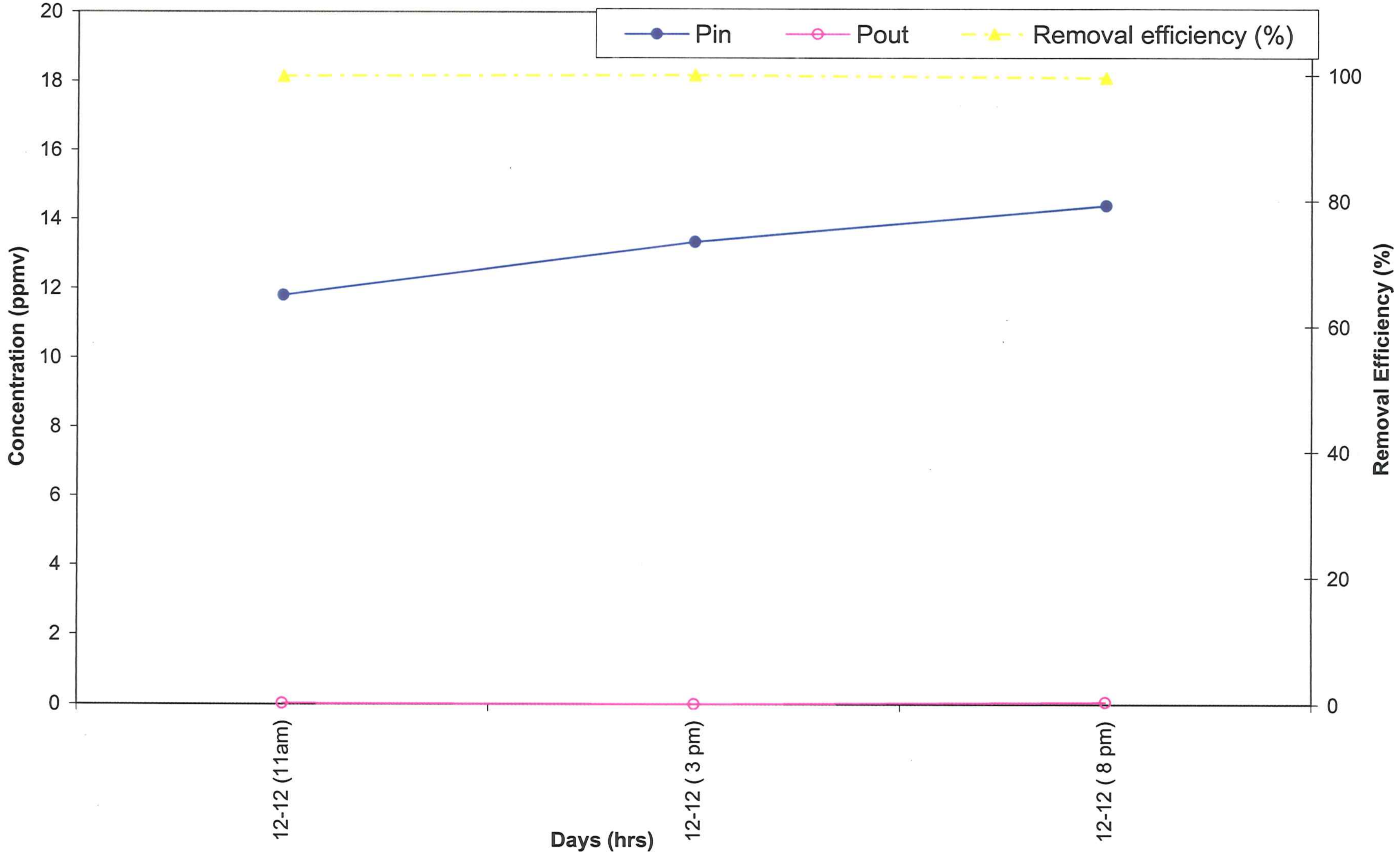


Figure 53. Removal of Carbonyl Sulfide in Biotrickling Filter

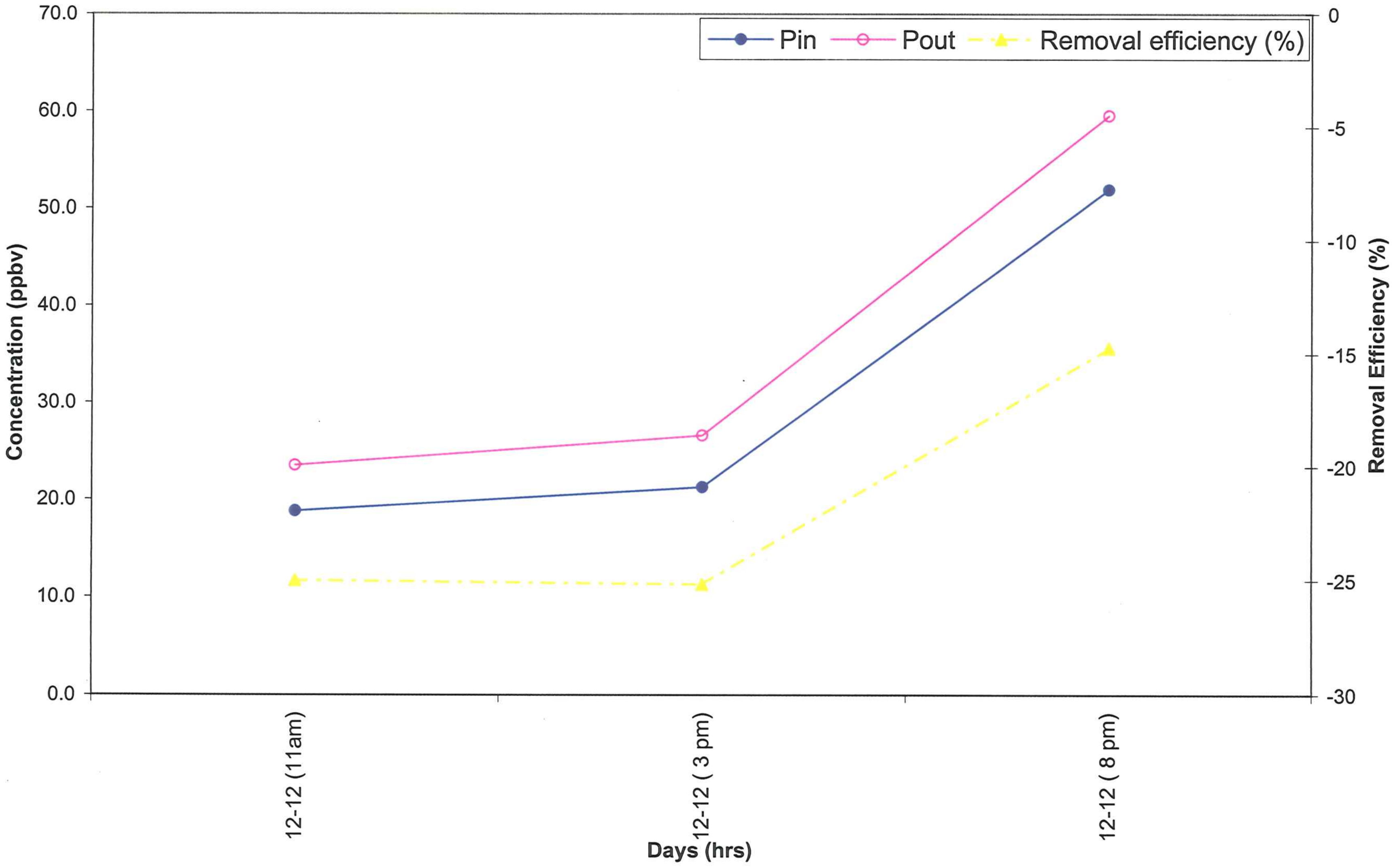


Figure 54. Removal of Methyl Mercaptan in Biotrickling Filter

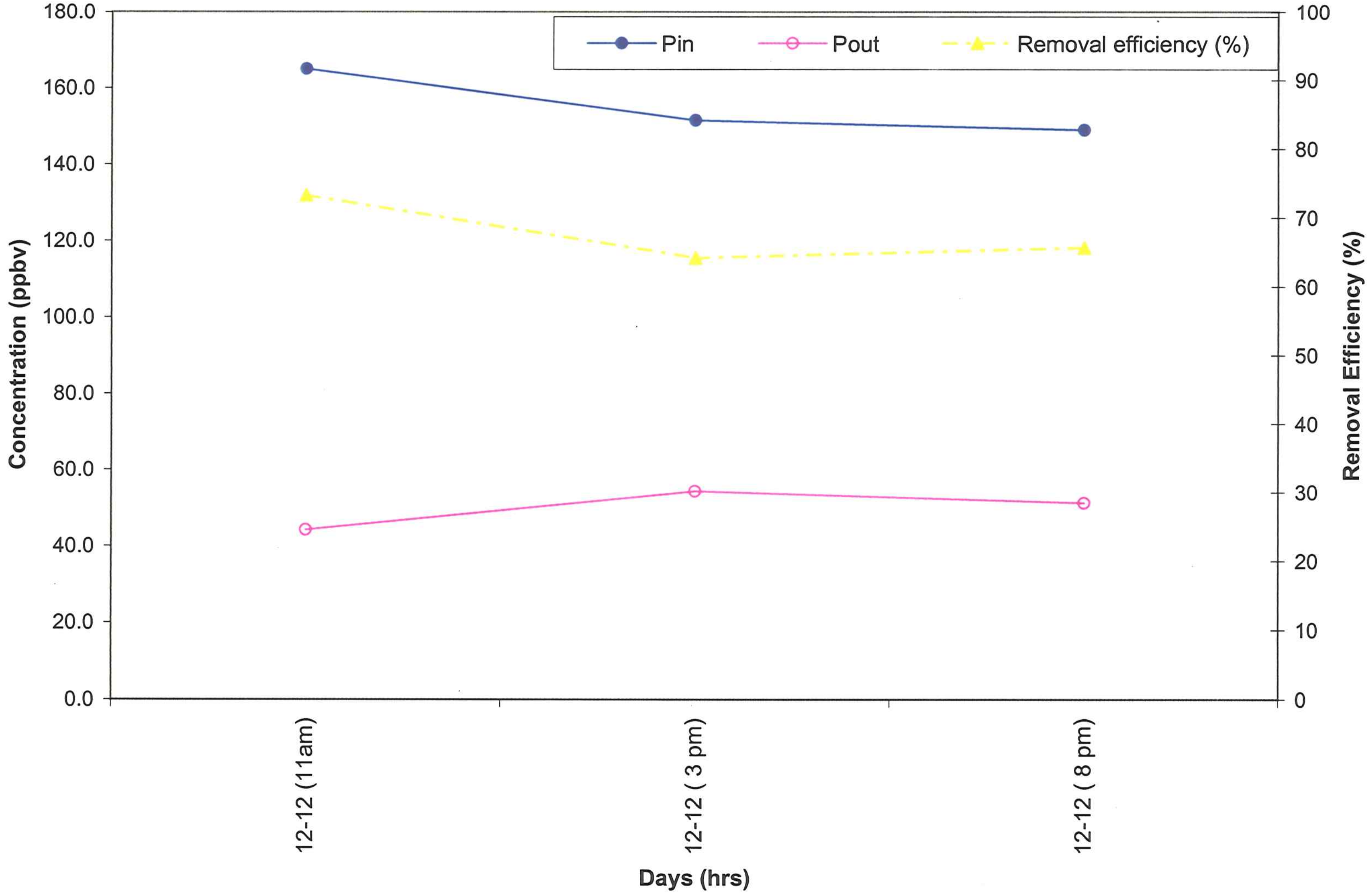


Figure 55. Removal of Dimethyl Sulfide in Biotickling Filter

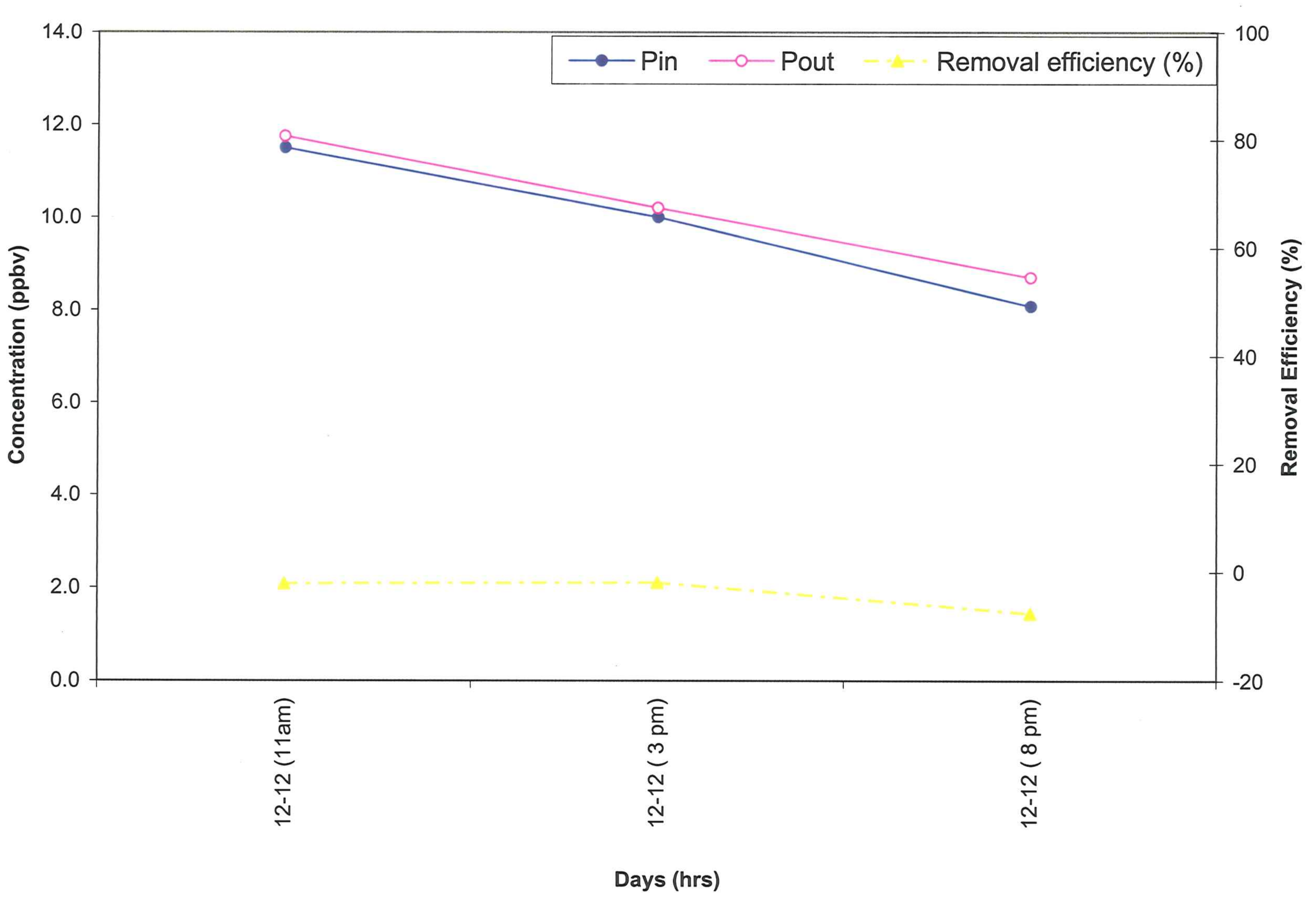


Figure 56. Removal of Carbon Disulfide in Biotrickling Filter