Development of Integrated Treatment Scheme of Adsorption and Biofiltration for VOCs Removal

Dissertation Defense for the Degree of Ph.D.

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Introduction

- **VOCs ?**

Volatile organic compounds (VOCs)

- They are found in the waste stream emitted from most processes employing organic or petroleum based solvents.

- A cost-effective technology: Biological treatment technology (biofiltration)

Introduction

For more successful application in industry

Challenges

Source Characteristics	Biofilter Maintenance
• Transient loading	• Biomass accumulation
• Non-use periods	• Microbial activity

Load fluctuation

Introduction

Load fluctuation

Solution = Buffer unit

Adsorption unit can be a buffer unit for a biofilter

Research Objectives

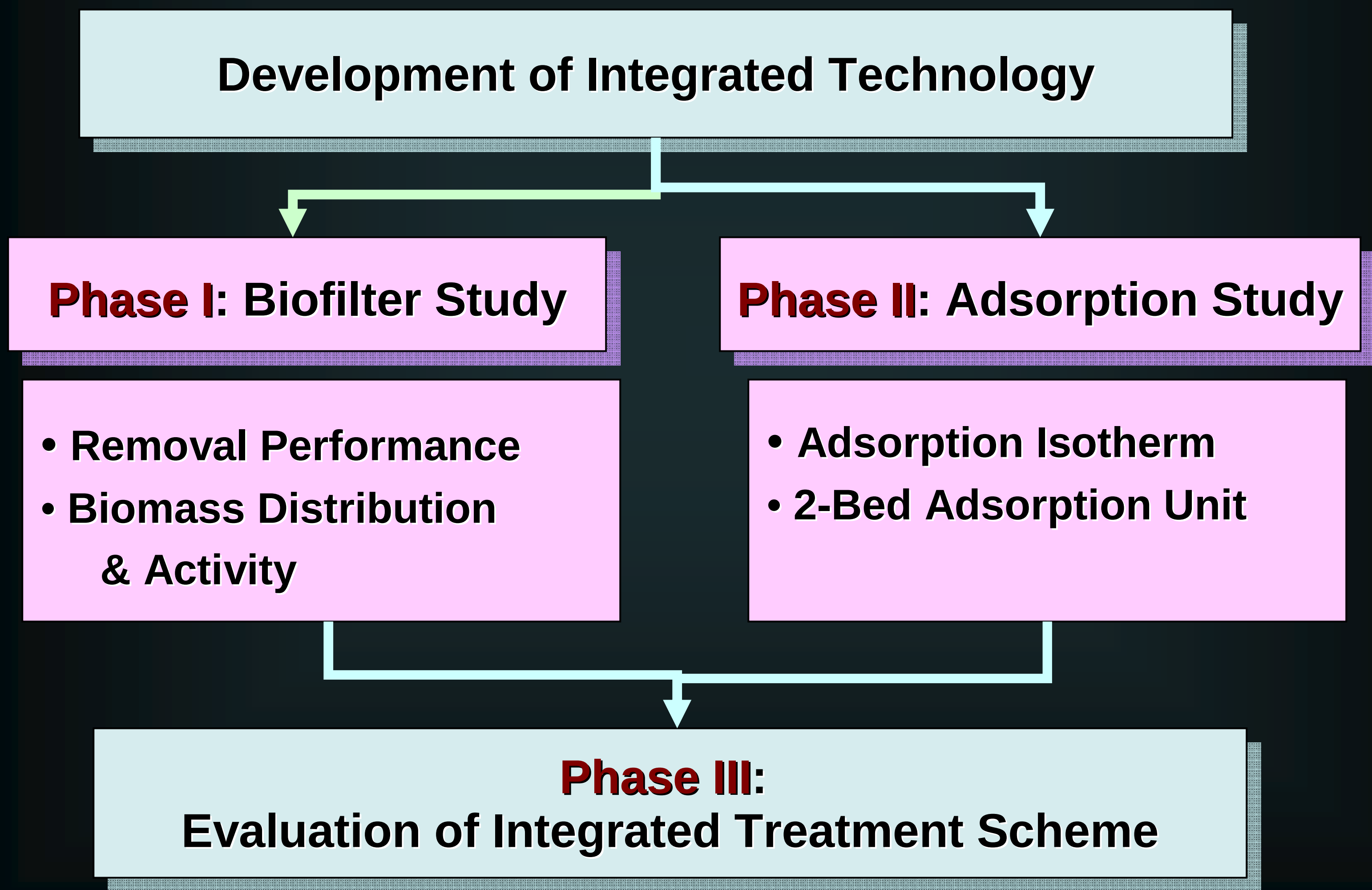
Main Objective

To develop an innovative technology for VOCs removal from waste gas with long-term, stable, high removal (>99%) performance

- **Proposed Technology: Integrated treatment scheme**

  Adsorption + Biofiltration

Research Objectives



Phase I: Biofilter Study

Phase I: Biofilter Study

- **Objectives**

To characterize Trickle Bed Air Biofilter (TBAB) performance treating different single VOCs under adverse operating conditions

Phase I: Biofilter Study

- **Objectives**

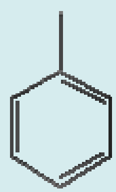
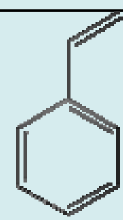
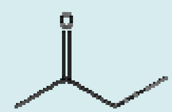
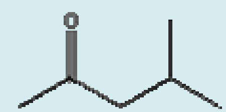
To characterize Trickle Bed Air Biofilter (TBAB) performance treating different single VOCs under adverse operating conditions

- **Specific Objectives**

- **Determine the critical loading capacity of TBAB for target VOCs**
- **Determine the impact of non-use periods on TBAB performance under different organic loading rates.**

Phase I: Biofilter Study

- **Target VOCs: (Paint booth industry)**

	Hydrophobic compounds		**Hydrophilic compounds**	
	Toluene	**Styrene**	**Methyl ethyl ketone** (MEK)	**Methyl isobutyl ketone** (MIBK)
				
K'_H	0.280	0.109	0.00194	0.00062
$LogK_{ow}$	2.58	3.16	0.28	1.09

K'_H = dimensionless Henry's law constant, K_{ow} = Octanol−water partition coefficient

Phase I: Biofilter Study

• Experimental Methods

- **Reactor :** Independent lab-scale TBAB

  Dimension: 76 mm (D) × 130 cm (L)

  Operating Temperature: 20°C

- **Media:** pelletized biological support media

Phase I: Biofilter Study

- **Experimental Strategies**

- **Backwashing** (as biomass control, 1 hour/ 1 week)
- **Non-use periods**
  - **Starvation** (without contaminant loading, 2 days/ 1 week)
  - **Stagnant** (without any flows, 2 days/ 1 week)

Phase I: Biofilter Study

- **Experimental Conditions**

	Toluene	Styrene	MEK	MIBK
Inlet Conc., *ppmv*	50 ~ 500	50 ~ 330	50 ~ 500	50 ~ 250
Loading rate *kg COD/m³·day*	0.7 ~ 7.03	0.64 ~ 3.17	0.7 ~ 7.03	1.09 ~ 5.43
EBRT, *min*	1.23	1.51 ~ 2.02	0.76	0.76

Phase I: Biofilter Study

- Results
  - VOC removal capacity
  - Correlation between critical loading rate & K_{ow}
  - Biofilter response after Backwashing & Non-use periods
    : Toluene, MEK
  - Biomass distribution
    : VS, EPS (proteins & total carbohydrates)

Phase I: Biofilter Study

- Results
  - VOC removal capacity
  - Correlation between critical loading rate & K_{ow}
  - Biofilter response after Backwashing & Non-use periods
    : Toluene, MEK
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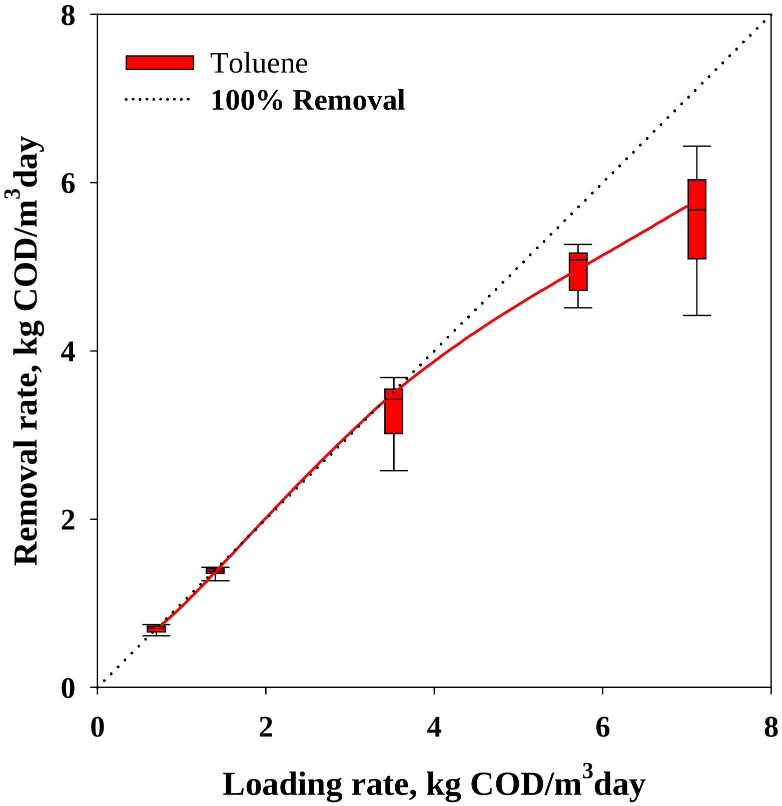
Phase I: Biofilter Study

- Results – VOC removal capacity (Backwashing)

Aromatic compounds

Toluene

- Critical loading
  3.5 kg COD/m³·day



Phase I: Biofilter Study

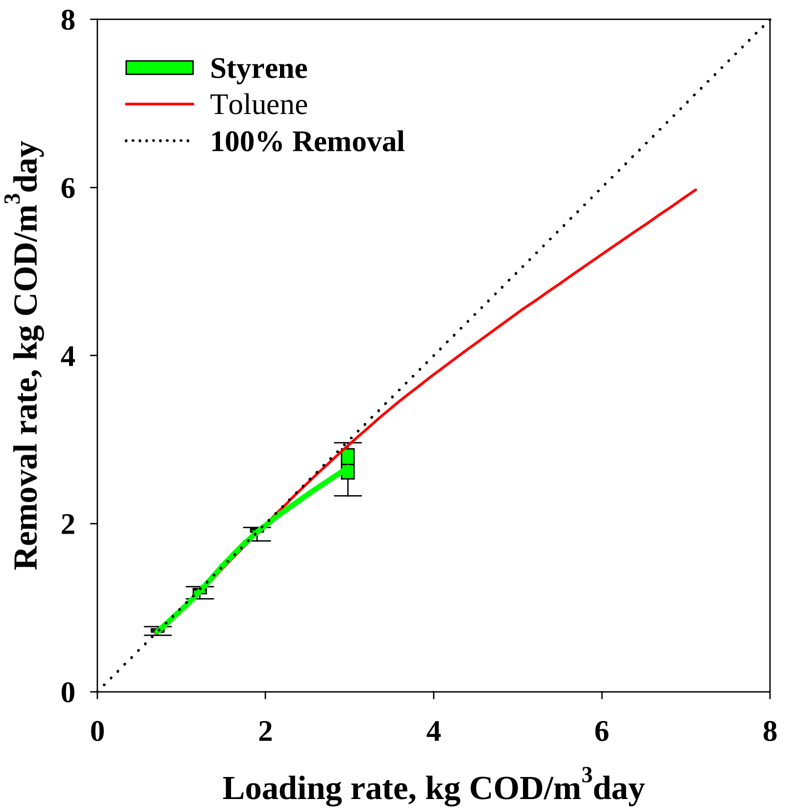
- Results – VOC removal capacity (Backwashing)

Aromatic compounds

Styrene

- Critical loading

  1.9 kg COD/m^3·day



Phase I: Biofilter Study

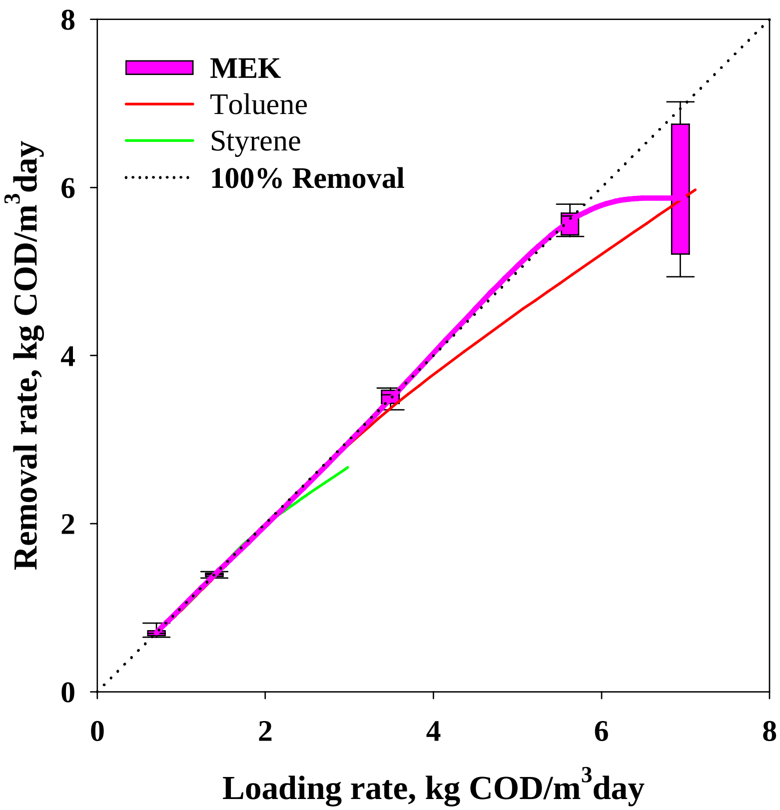
- Results – VOC removal capacity (Backwashing)

Oxygenated compounds

MEK

- Critical loading

  5.6 kg COD/m^3·day



Phase I: Biofilter Study

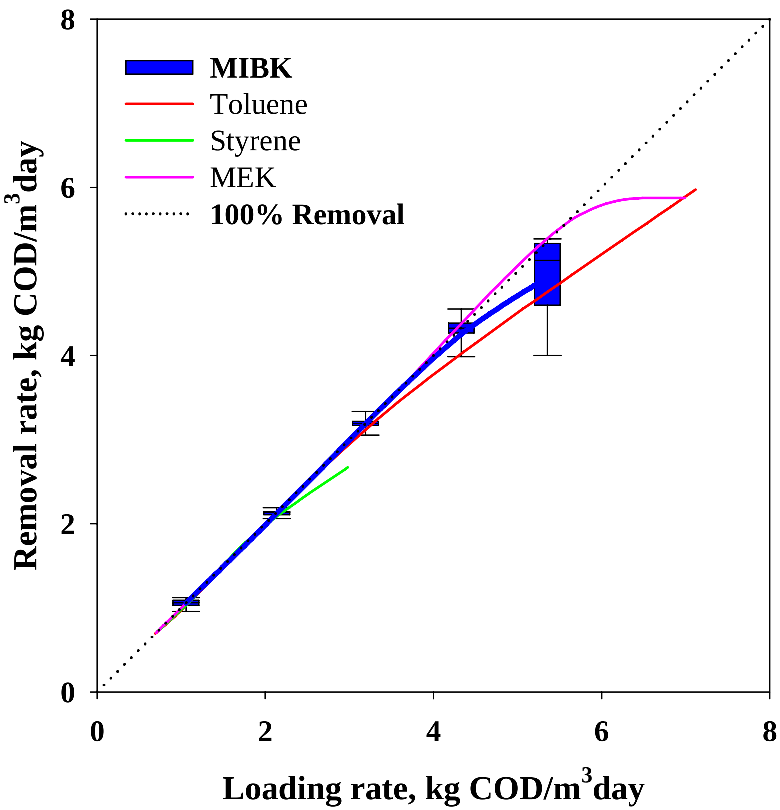
- **Results – VOC removal capacity (Backwashing)**

Oxygenated compounds

MIBK

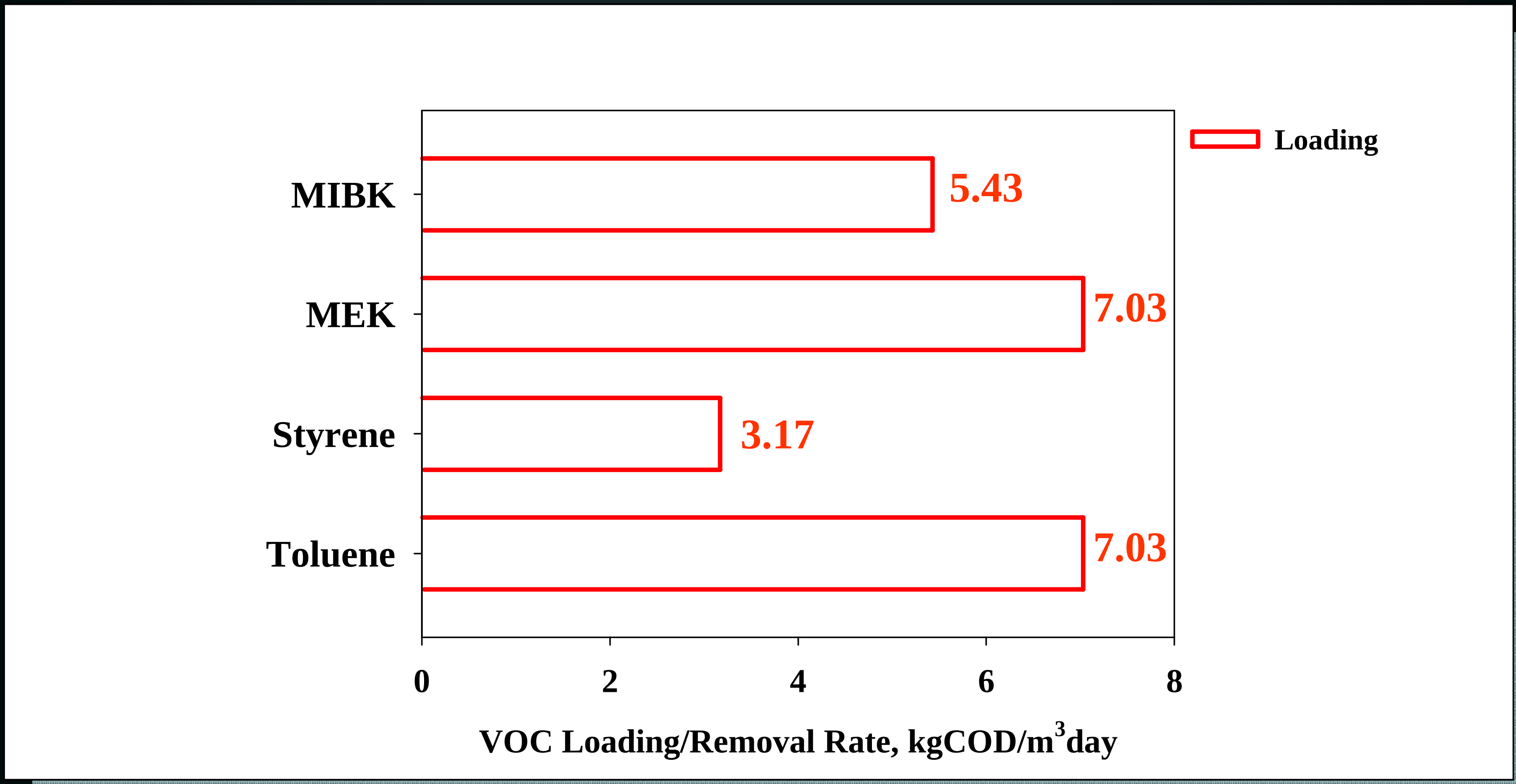
- Critical loading

  4.3 kg COD/m³·day



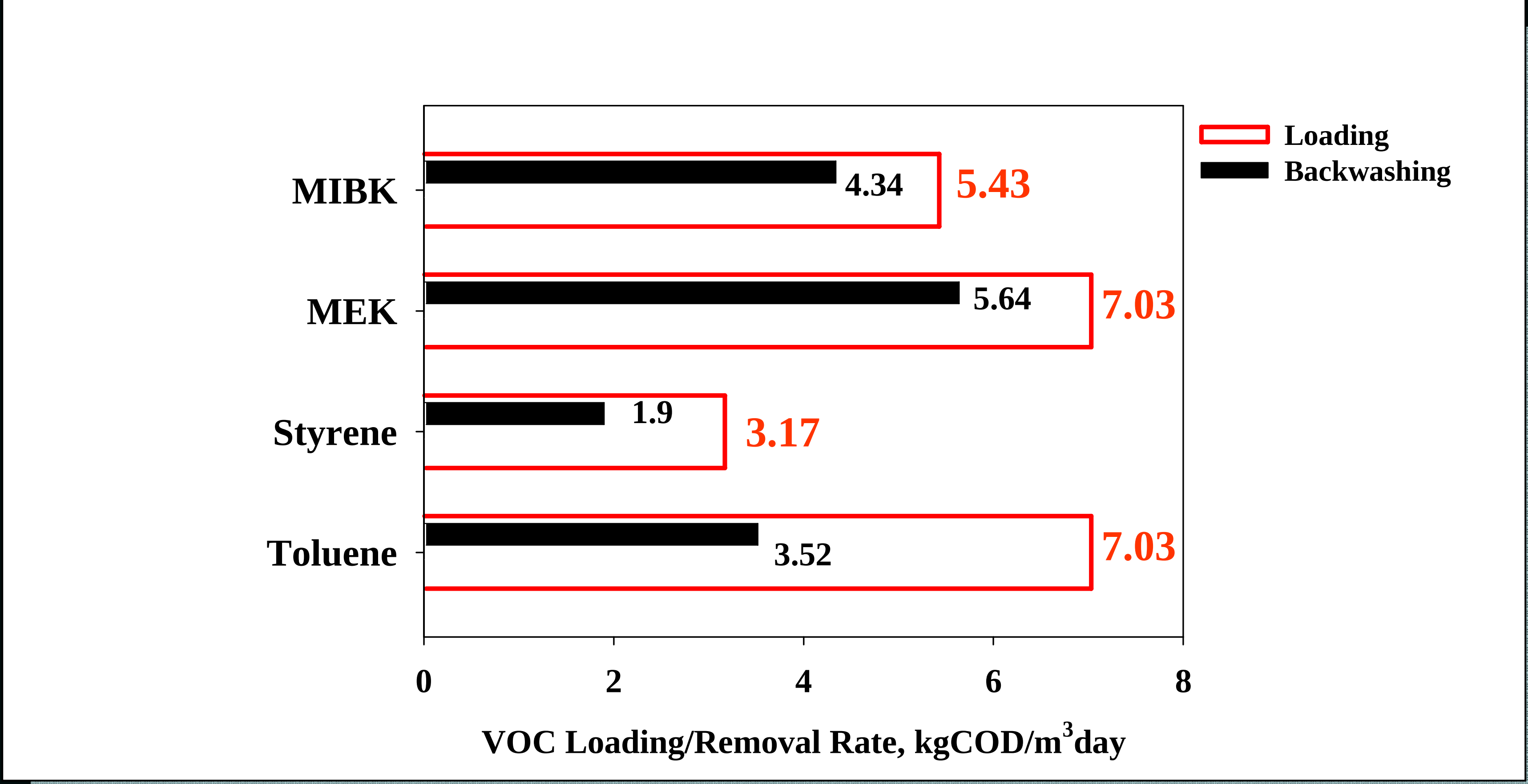
Phase I: Biofilter Study

- Results – Comparison of VOC removal capacity



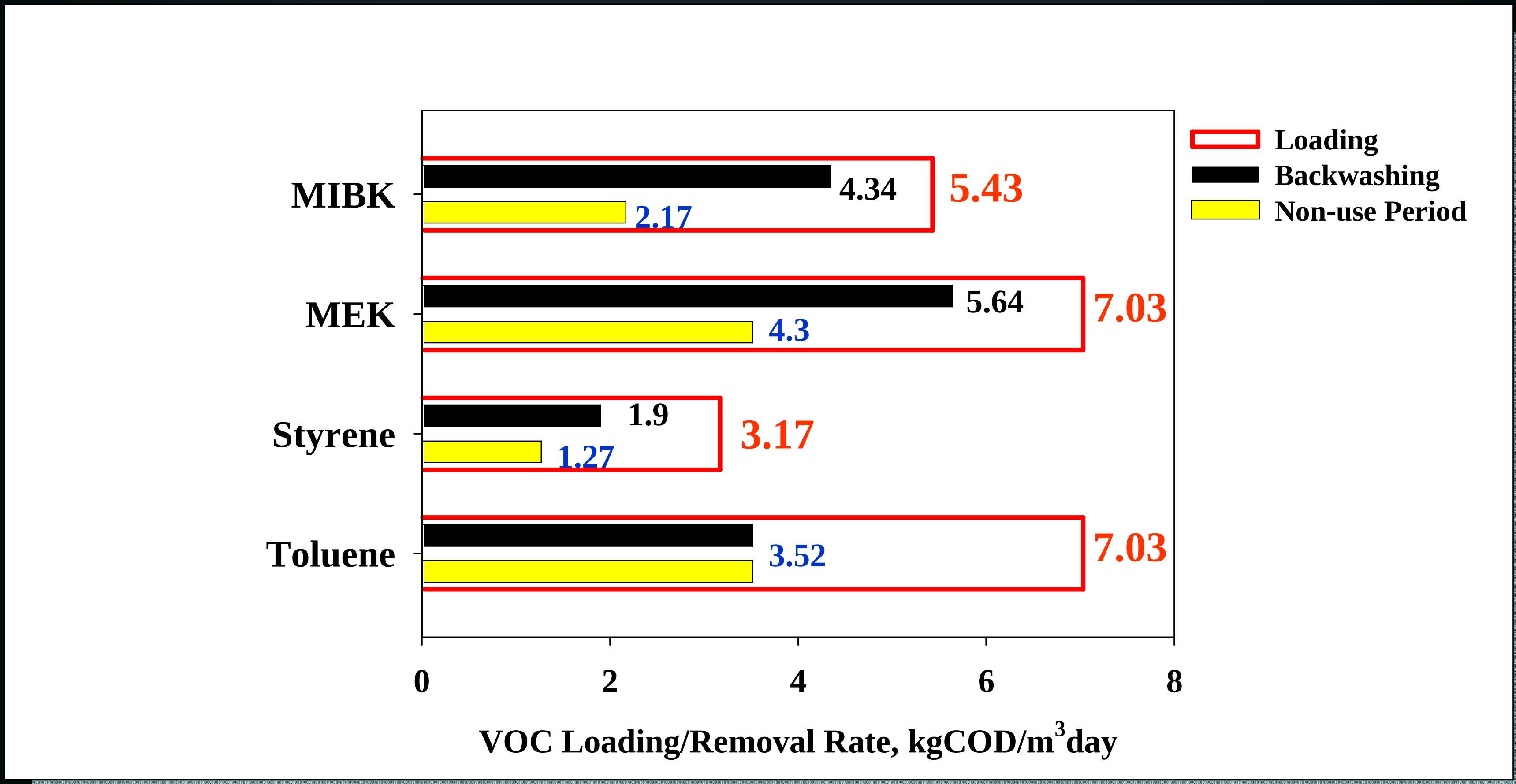
Phase I: Biofilter Study

- Results – VOC removal capacity



Phase I: Biofilter Study

- Results – VOC removal capacity



Phase I: Biofilter Study

- **Results**

  - VOC removal capacity

  - Correlation between critical loading rate & VOC properties

  - Biofilter response after Backwashing & Non-use periods

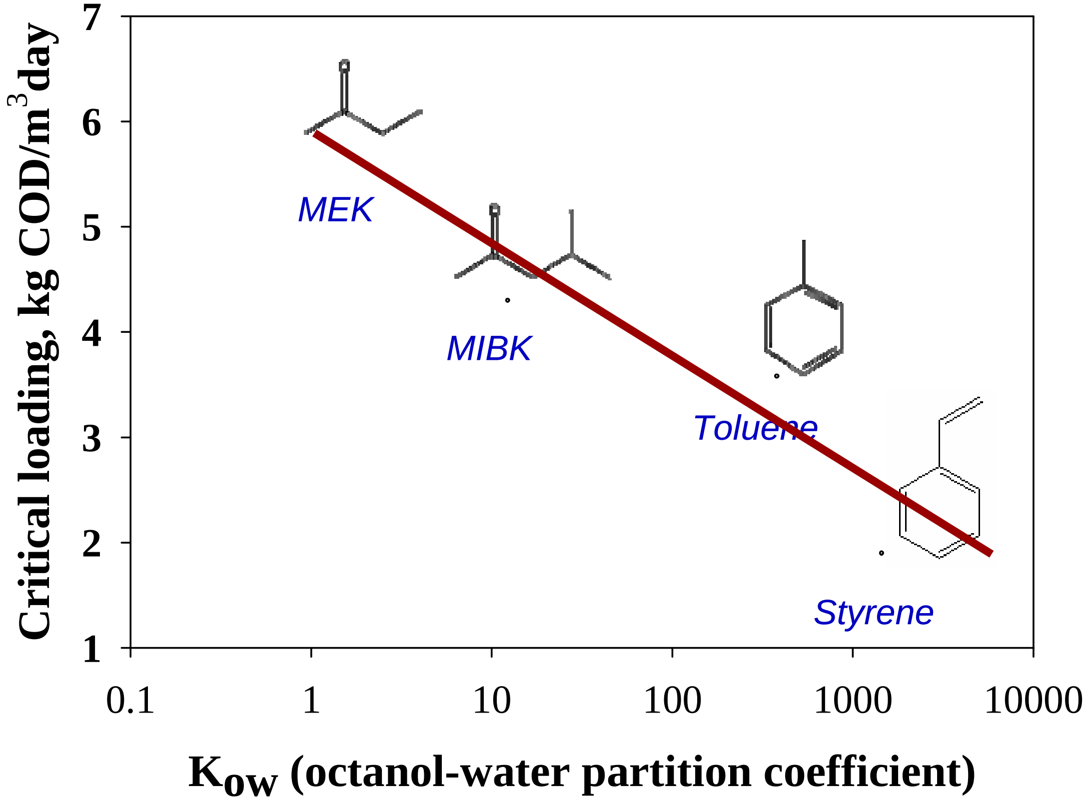
  : Toluene, MEK

  - Biomass distribution

  : VS, EPS (proteins & total carbohydrates)

Phase I: Biofilter Study

- Results – Critical loading vs. Kow

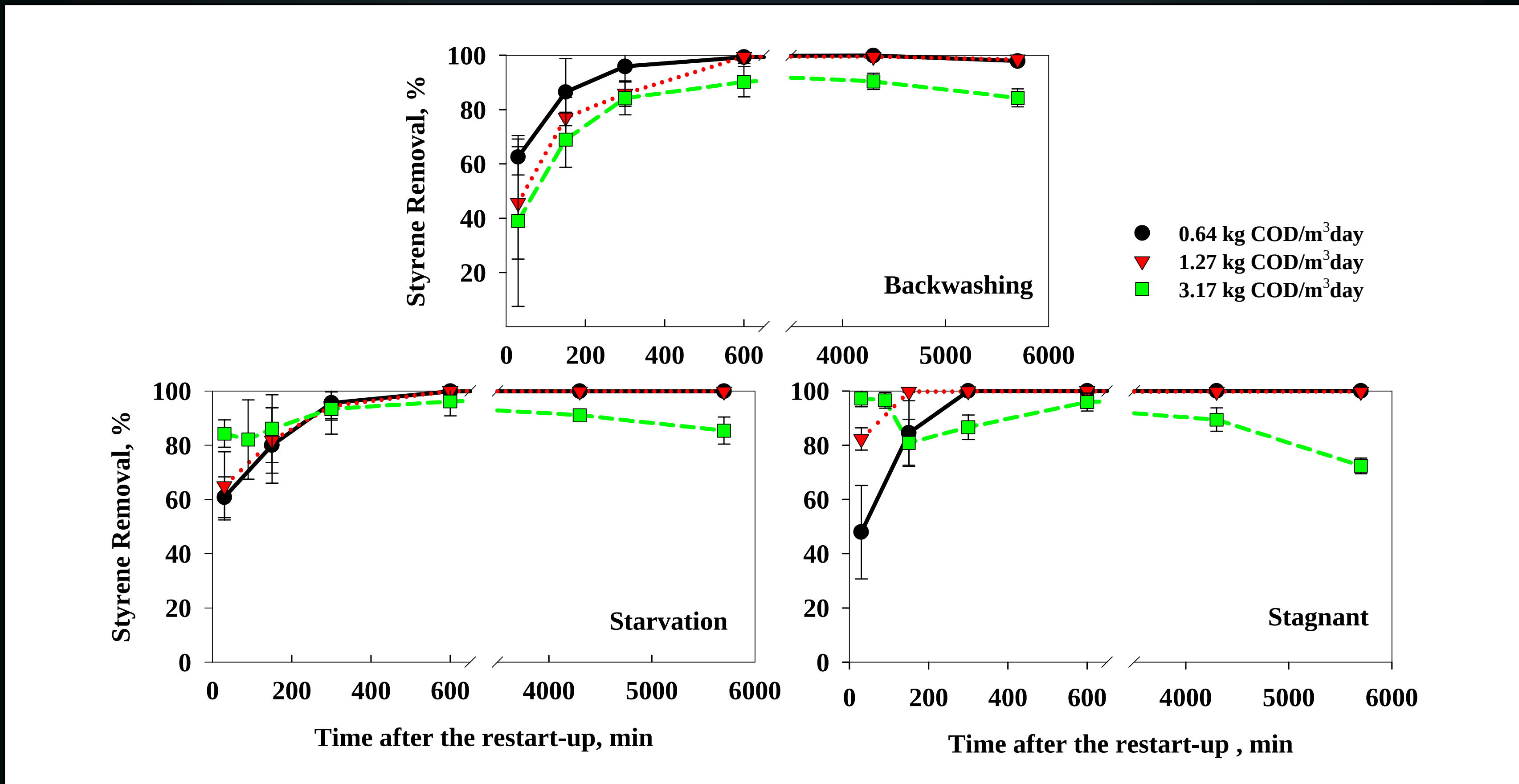


Phase I: Biofilter Study

- **Results**
  - **- VOC removal capacity**
  - **- Correlation between critical loading rate & K_{ow}**
  - **- Biofilter response after Backwashing & Non-use periods**
    - **: Styrene, MEK**
  - **- Biomass distribution**
    - **: VS, EPS (proteins & total carbohydrates)**

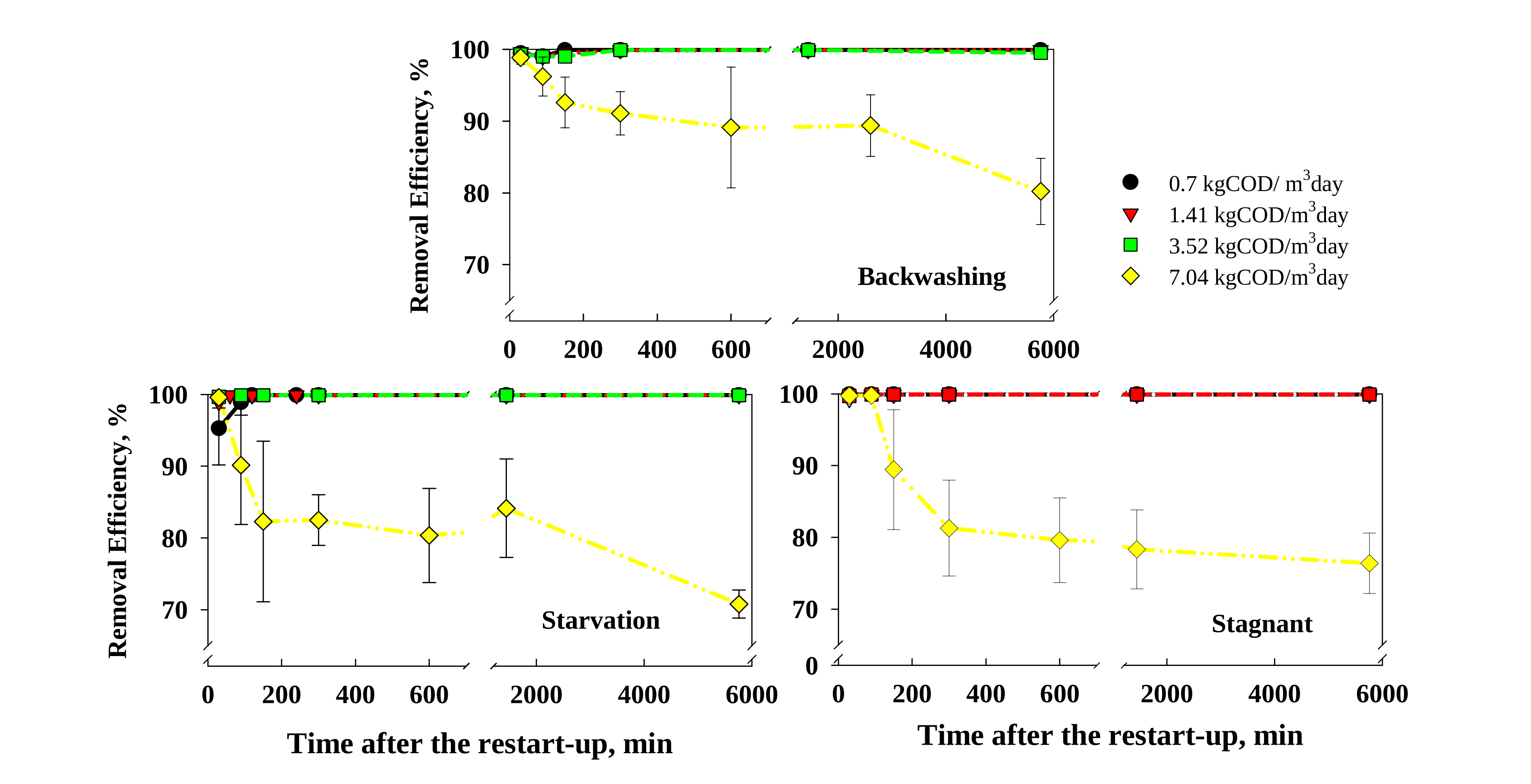
Phase I: Biofilter Study

- Results – Styrene biofilter response



Phase I: Biofilter Study

- Results – MEK biofilter response

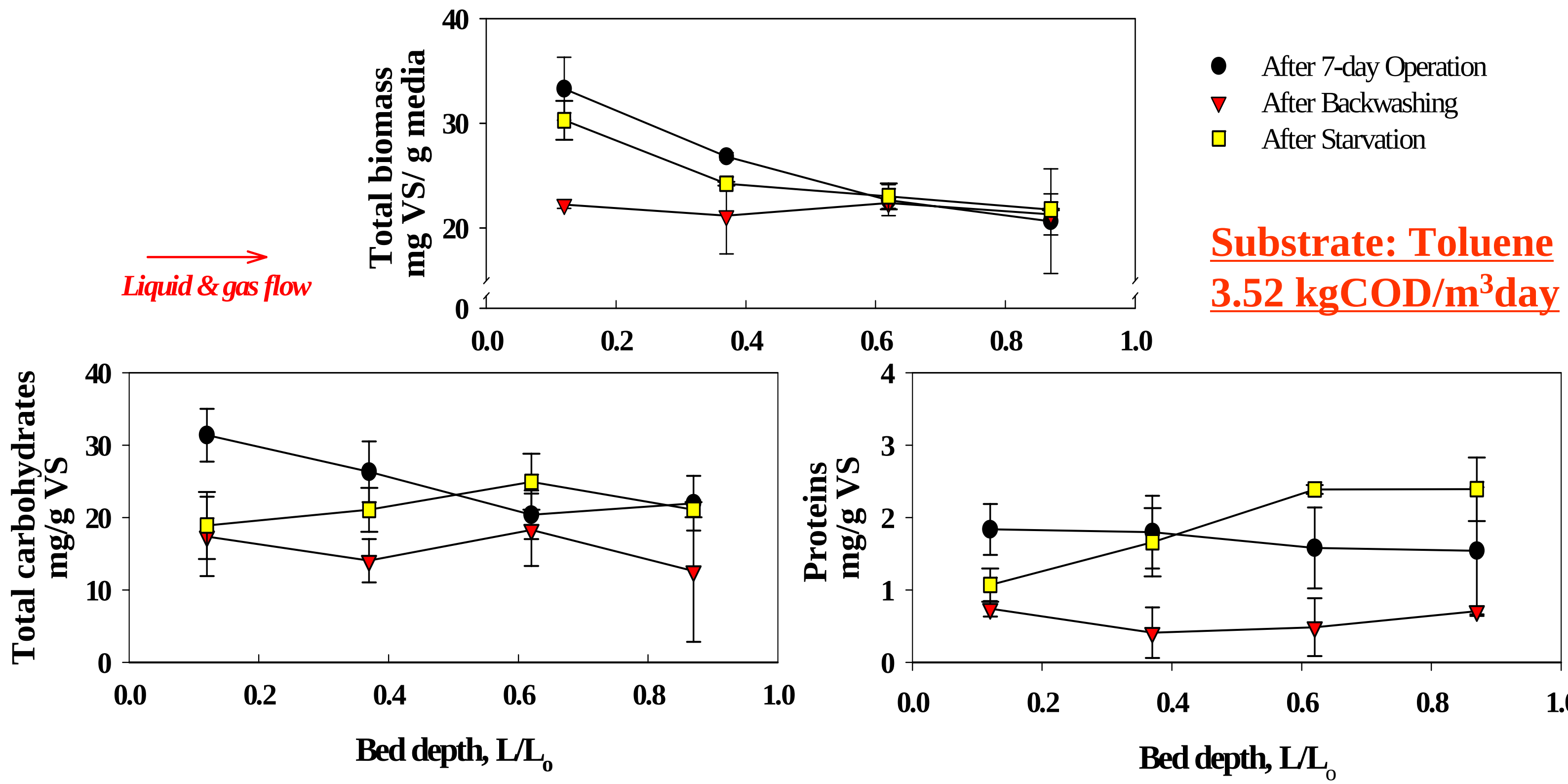


Phase I: Biofilter Study

- Results
  - VOC removal capacity
  - Correlation between critical loading rate & K_{ow}
  - Biofilter response after Backwashing & Non-use periods
    : Toluene, MEK
  - Biomass distribution
    : VS, EPS (proteins & total carbohydrates)

Phase I: Biofilter Study

- **Results – Biomass distribution**



Substrate: Toluene
3.52 kgCOD/m^{3}day

Phase I: Biofilter Study

- **Results**

  - VOC removal capacity
  - Correlation between critical loading rate & K_{ow}
  - Biofilter response after Backwashing & Non-use periods
    : Toluene, MEK
  - Biomass distribution
    : VS, EPS (proteins & total carbohydrates)
  -

Phase I: Biofilter Study

- **Conclusion and Summary**

Experimental findings supported the handling limitation of performance of the current biofiltration system

1. **Up to the critical VOC loading rate, the backwashing was effective biomass control to attain consistently high removal performance.**

2. **Non-use periods can be considered as another means of biomass control at lower VOC loading rate.**

3. **Reacclimation was a critical factor in biofilter peformance. After non-use periods, the active biomass affects biofilter response.**

Phase I: Biofilter Study

- **Conclusion and Summary**

Experimental findings supported the handling limitation of performance of the current biofiltration system

4. **Biofilter performance linked with VOCs removal and biomass growth depended on the physicochemical properties of VOCs.**

5. **Biofilter performance was affected by microbial activity and biomass distribution.**

Phase II: Adsorption Study

Phase II: Adsorption Study

- **Objectives**

To development of 2-bed adsorption process for dampening contaminant fluctuations

- **Specific Objectives**

• Determine the adsorption isotherms of VOCs of concern
• Design and evaluate a 2-fixed bed adsorption unit

Phase II: Adsorption Study

Adsorption Isotherm

Phase II: Adsorption Study

Adsorption Isotherm

- **Experimental Methods**

- **Adsorbate:** Toluene, MEK, MIBK
- **Adsorbent:**
  - BPL-Bituminous based
  - OVC-Coconut based
- **Method:** Simple constant volume method

Phase II: Adsorption Study

Adsorption Isotherm

- **Simple Constant Volume Method**

- **Using "Gas sample bag",**

  a 10-L Tedlar gas sample bag
- **Using "Calibrated 6-L canister"**

  for provide 6-L air into bags

Phase II: Adsorption Study

Adsorption Isotherm

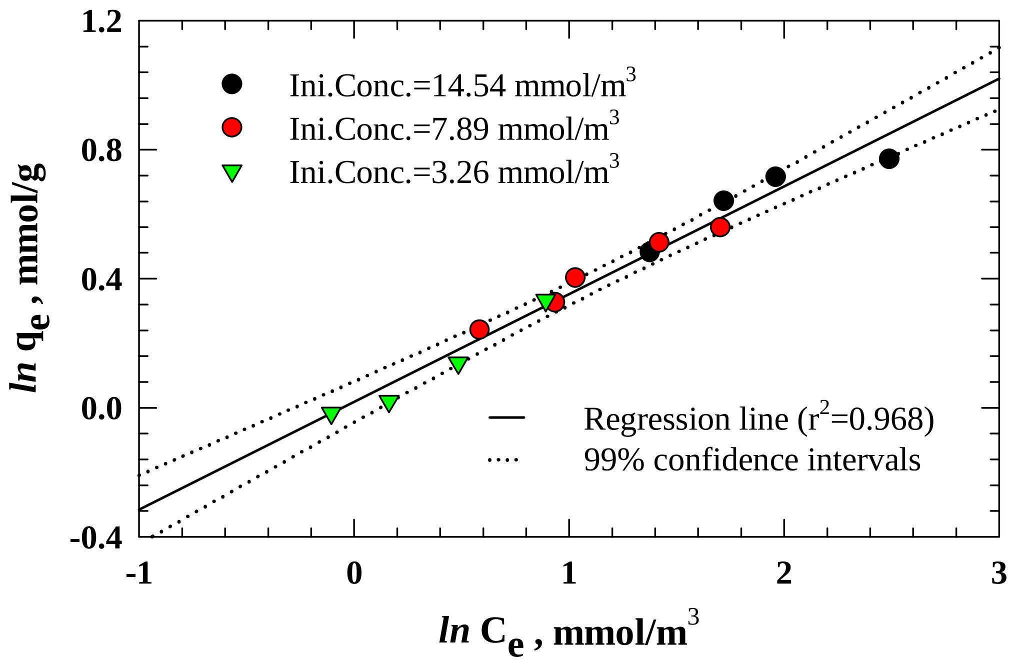
- Results: Single solute Isotherm

Phase II: Adsorption Study

Adsorption Isotherm

- **Results: Single solute Isotherm**

• **MEK Adsorption on OVC**

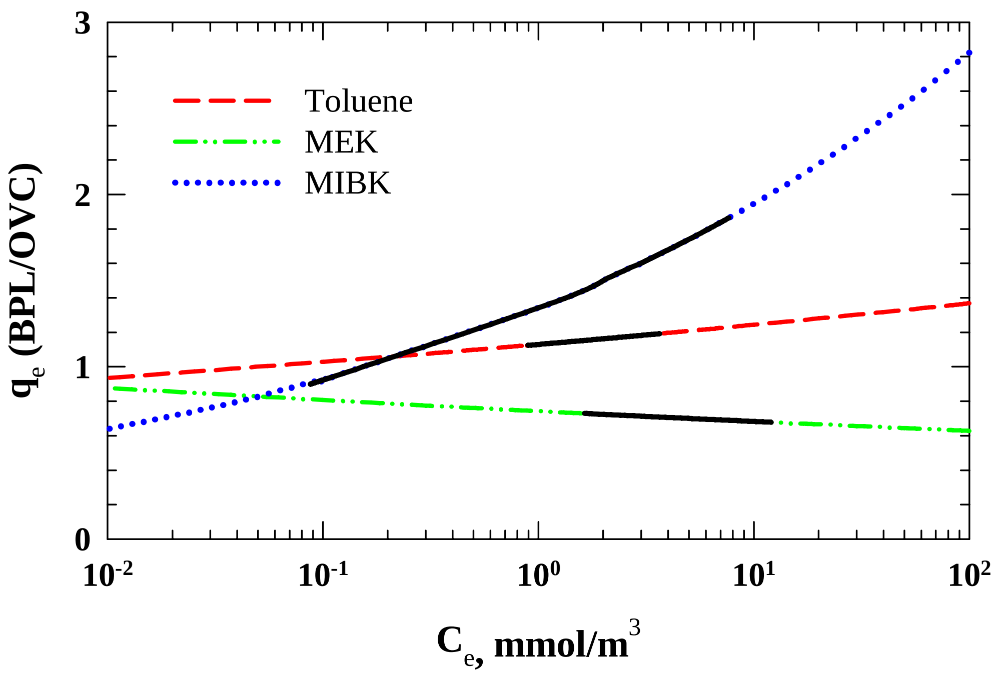


Phase II: Adsorption Study

Adsorption Isotherm

- **Results: Single solute Isotherm**

- **Comparison of activated carbon adsorption capacity**



*** Adsorbent**
Pore size distribution

*** Adsorbate**
Interaction potentials

Phase II: Adsorption Study

Adsorption Isotherm

- Results: Ternary Isotherm

  - Adsorbent: BPL

  - Adsorbate: Toluene, MEK, MIBK

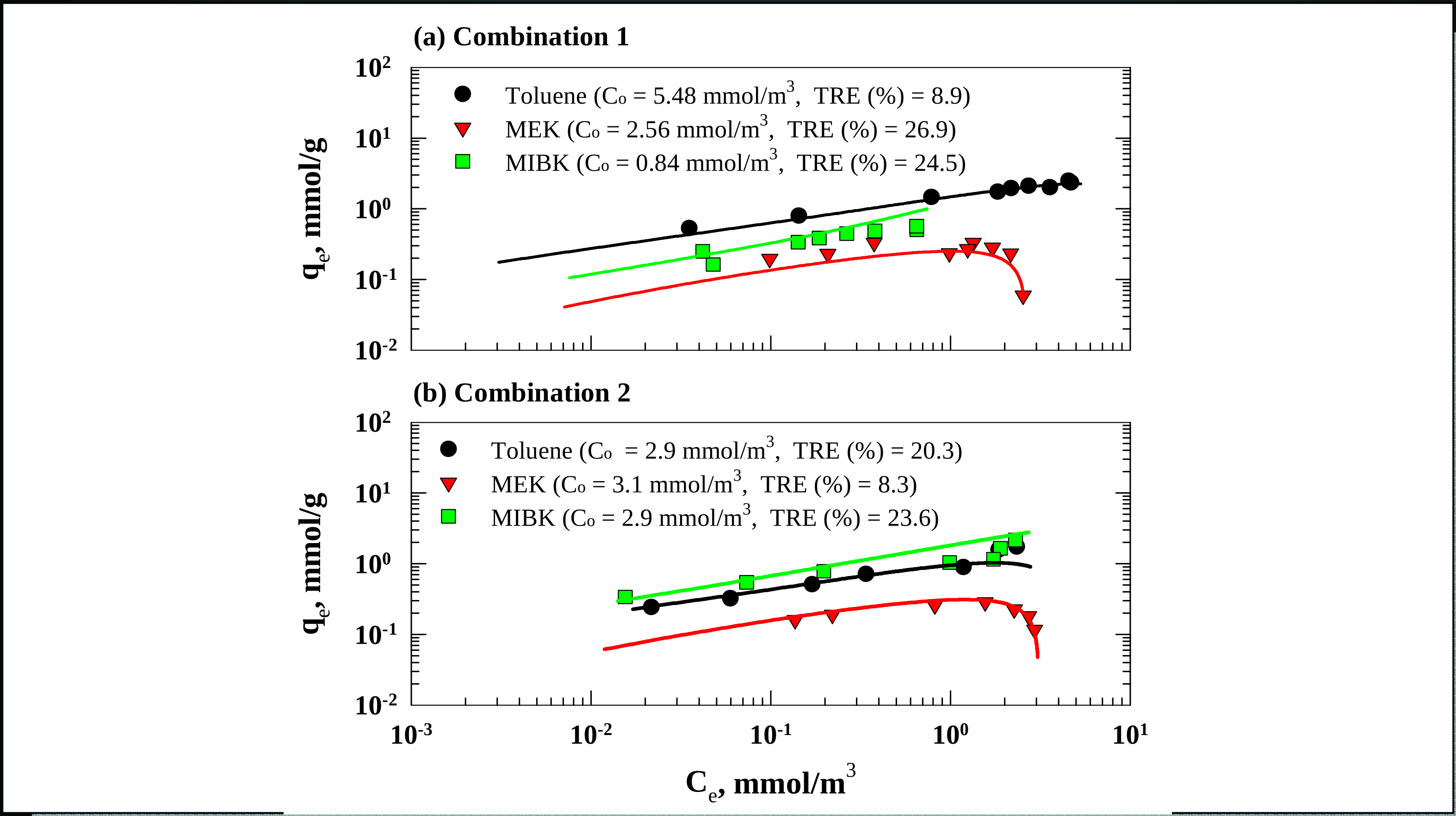
  - Method: simple constant volume method

  - Simulation: IAST

Phase II: Adsorption Study

Adsorption Isotherm

- **Results: Ternary Isotherm**



Phase II: Adsorption Study

Adsorption Isotherm

- **Conclusion and Summary**

Single and ternary adsorption isotherms were successfully determined by employing a simple constant volume method

1. **For single solute adsorption, the pore size distribution of adsorbents was found to affect their adsorption capacities; its effect was dependents on the solute concentration.**

2. **The ideal adsorbed solution theory (IAST) was found to accurately predicts the ternary adsorption isotherms.**

Phase II: Adsorption Study

2-Bed Adsorption

Phase II: Adsorption Study

2-Bed Adsorption

- **Concept**

• Conceptually simple process to PSA
• PSA (Pressure Swing Adsorption) :
→ A technology for separation and purification for gas mixtures
→ 4 Steps for operational function

Feeding (Adsorption)
↓
Depressurization
↓
Purging (desorption) — Regeneration
↓
Repressurization

Phase II: Adsorption Study

2-Bed Adsorption

- **Concept**

• Hypothetically, if adsorption rate is equal to its desorption rate
→ Operational function is simplified to a 2-step

Phase II: Adsorption Study

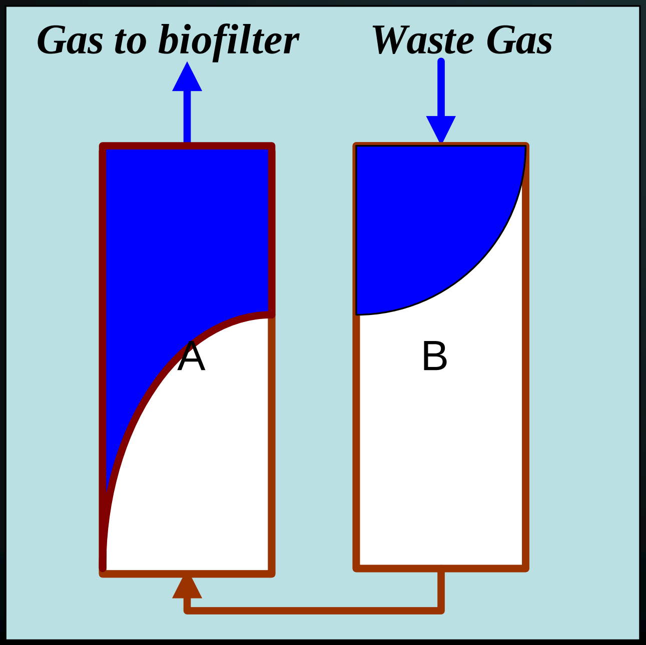
2-Bed Adsorption

- **Concept**

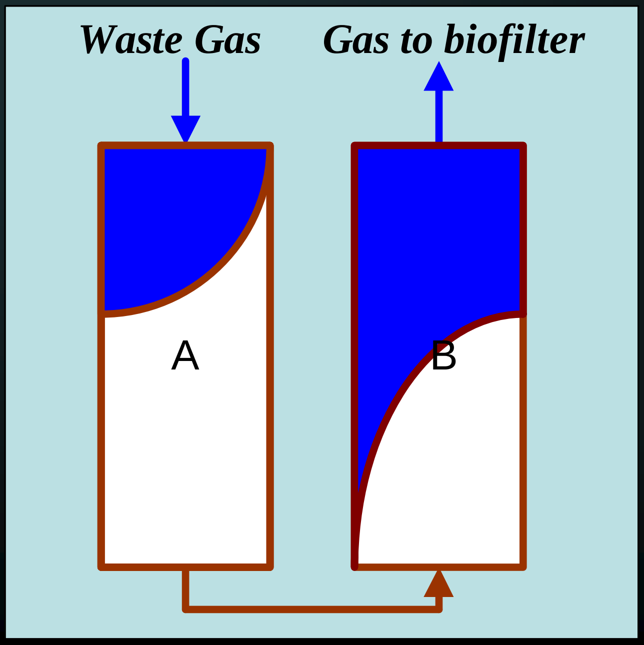
• Driving force for desorption: decrease in contaminant gas pressure

→ Each bed will not be fully saturated with adsorbate

Clockwise



Counterclockwise



Phase II: Adsorption Study

2-Bed Adsorption

- **Concept**

Will serve as

- Polishing unit during the initial acclimation period of the biofilter
- Buffer unit in load fluctuation
- Feeding source without any feeding phase during non-use periods

Phase II: Adsorption Study

2-Bed Adsorption

- **Experimental Methods**

- 2 Beds
- Dimension : 2.5 cm (D) × 20 cm (L)
- Duration of one cycle : 8 hours
- EBRT: 5.6 sec (2.2 L/min)

- Adsorbate : Toluene
- Adsorbent : GAC (BPL 6 × 16)

* Design

Phase II: Adsorption Study

2-Bed Adsorption

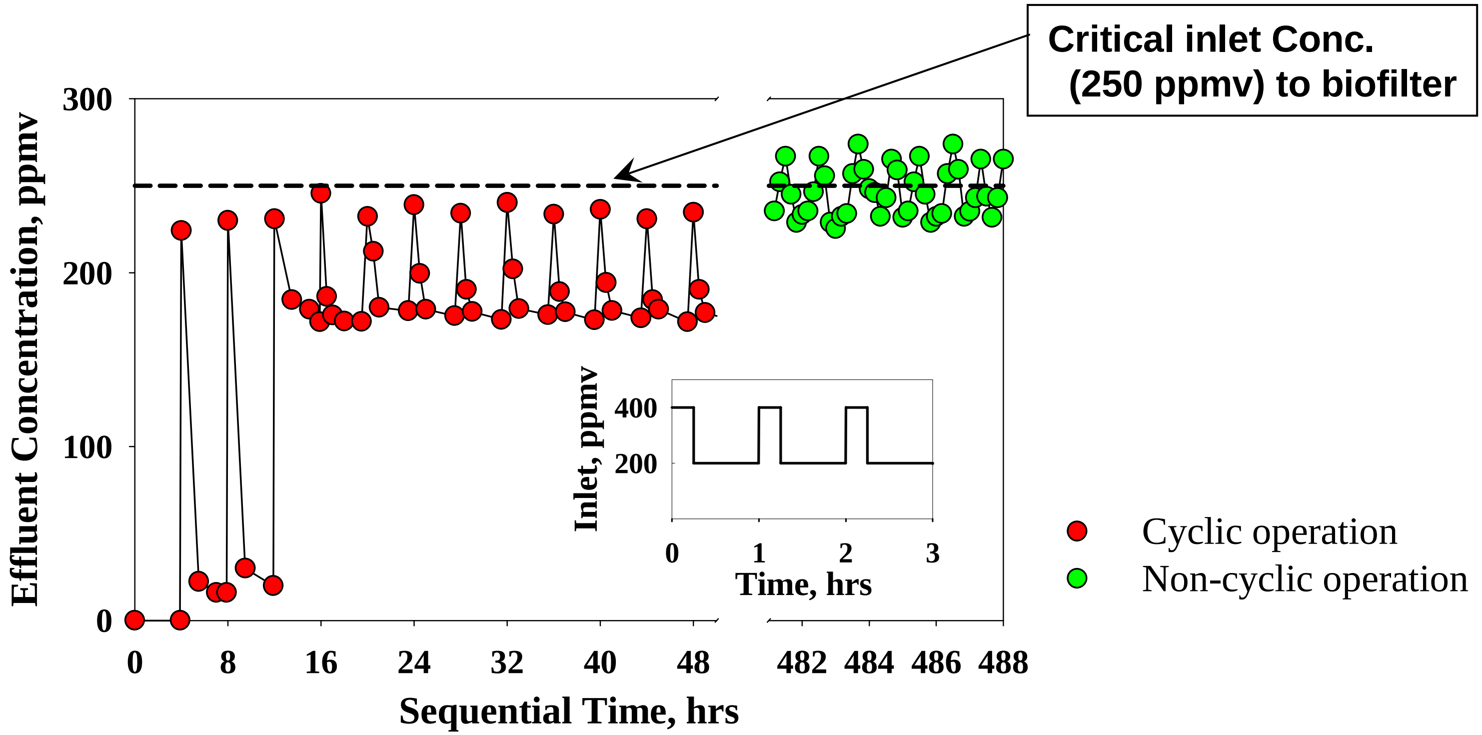
- Results

Phase II: Adsorption Study

2-Bed Adsorption

- **Results**

• Efflunet response to cyclic operation and non-cyclic operation



Phase II: Adsorption Study

2-Bed Adsorption

- **Conclusion**

- **The adsorption system consisted of two fixed beds which are alternately pressurized and depressurized was simply achieved.**
- **The operating adsorption and desorption cycles for the unit yielded constant loading conditions that can be treated effectively in the biofiltration**

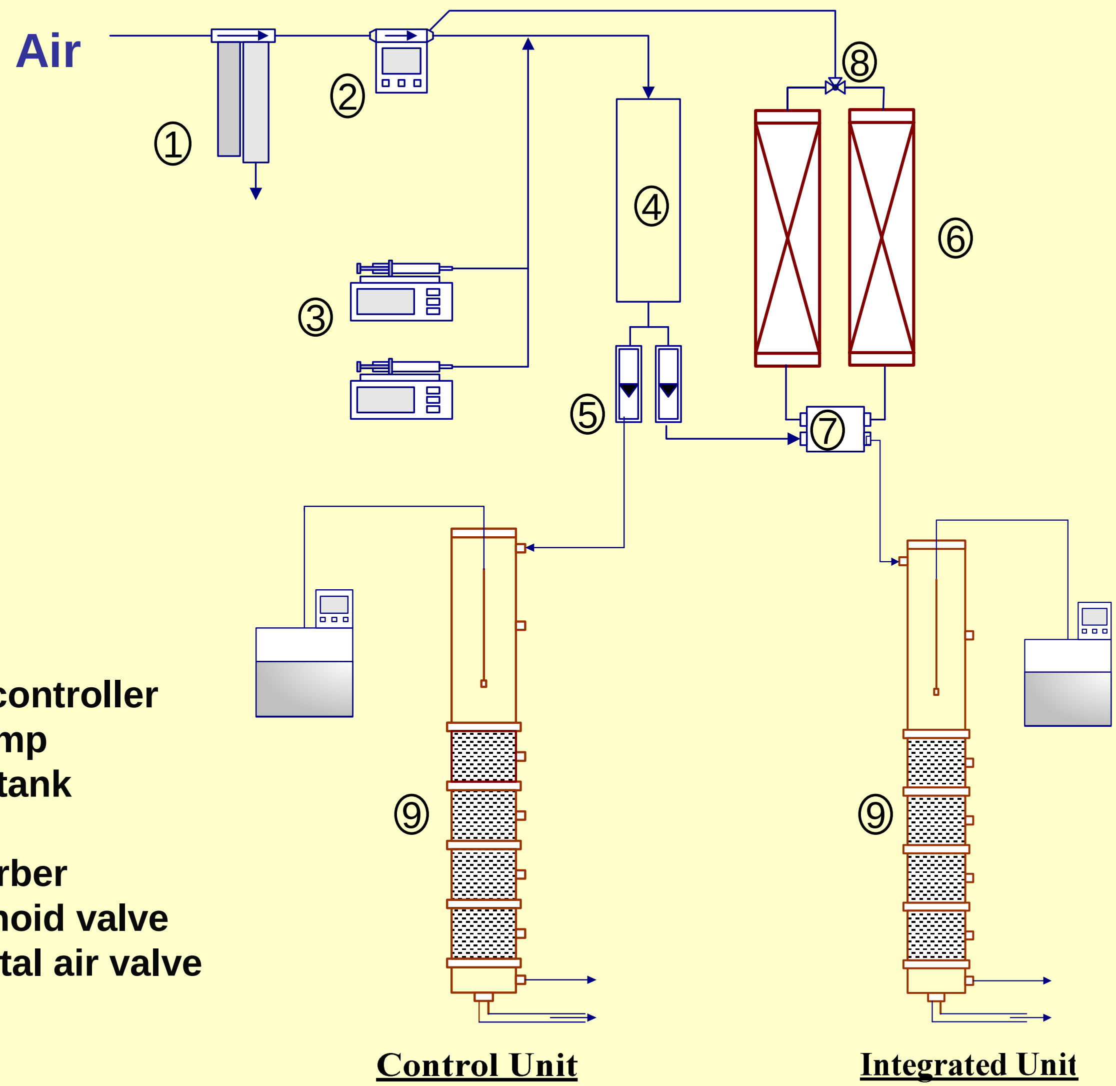
Phase III: Integrated Treatment Scheme

Phase III: Integrated Treatment Scheme

- **Objectives**

To evaluate the performance of the integrated treatment scheme of a biofilter preceded by a 2-fixed bed adsorption unit

Phase III: Integrated Treatment Scheme



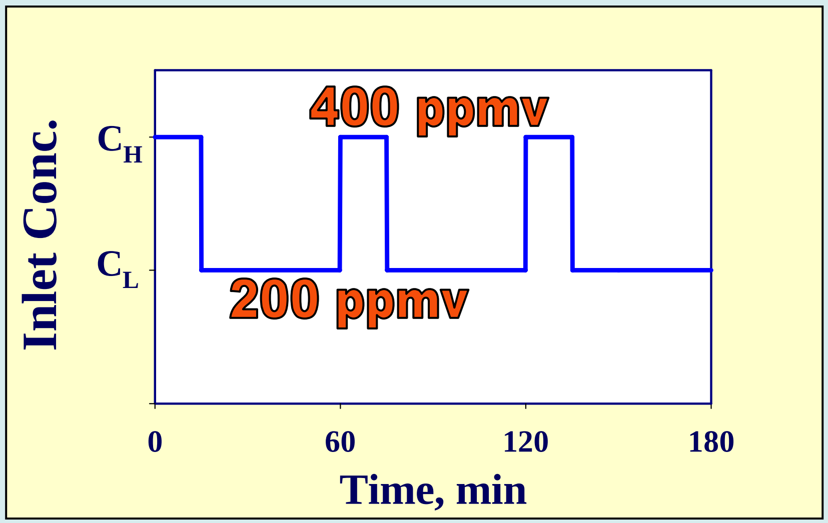
1. Air cleaner
2. Mass flow controller
3. Syringe pump
4. Equalizing tank
5. Flow meter
6. 2-bed adsorber
7. 4-way solenoid valve
8. Supplemental air valve
9. Biofilter

Phase III: Integrated Treatment Scheme

- **Experimental Methods**

• **Targeted VOC:** Toluene

• **Feeding condition:** Square wave change of inlet concentration
- Base = 200 ppmv
- Peak = 400 ppmv (15 mins / hour)
- Average conc. : 250 ppmv
- Average load. : 3.5 kg COD/m^3·day

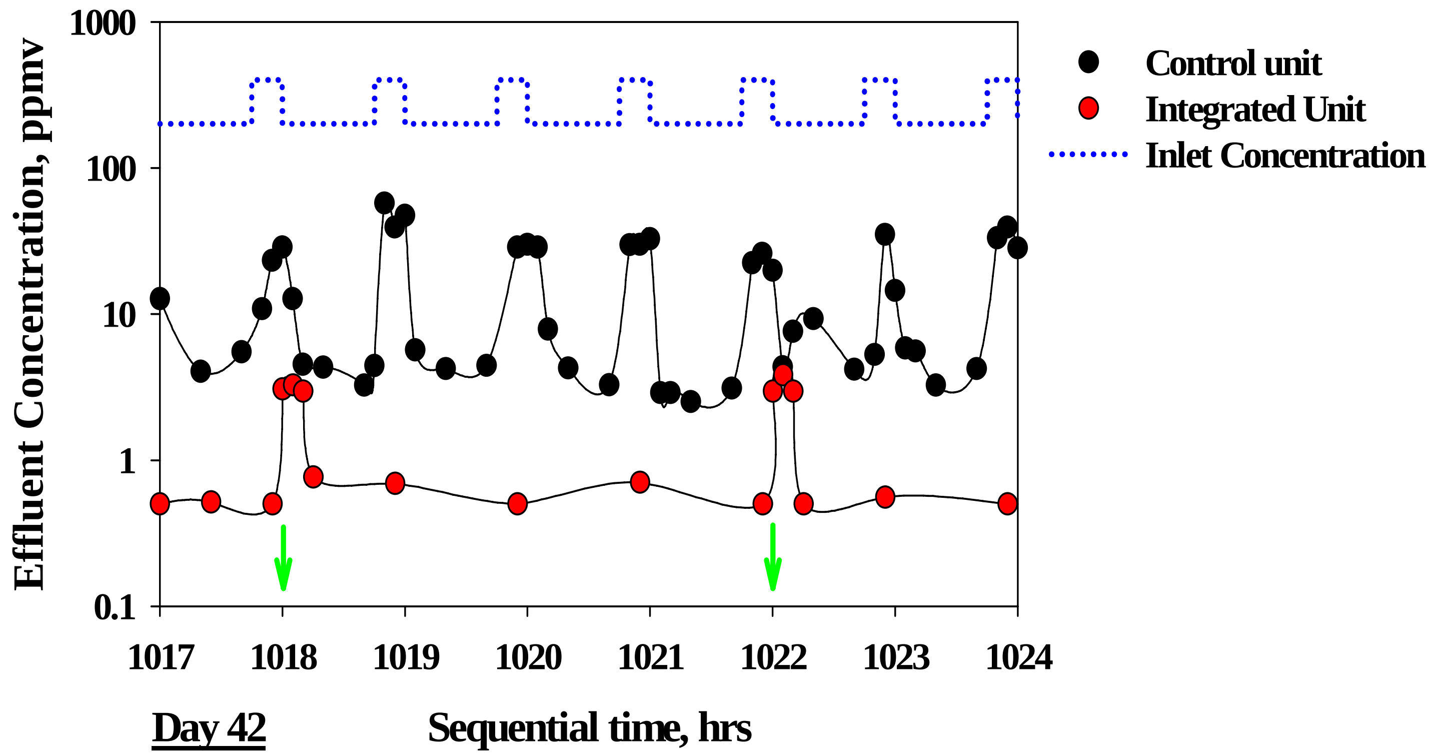


Phase III: Integrated Treatment Scheme

- Results: Toluene removal performance

Phase III: Integrated Treatment Scheme

- **Results: Toluene removal performance**

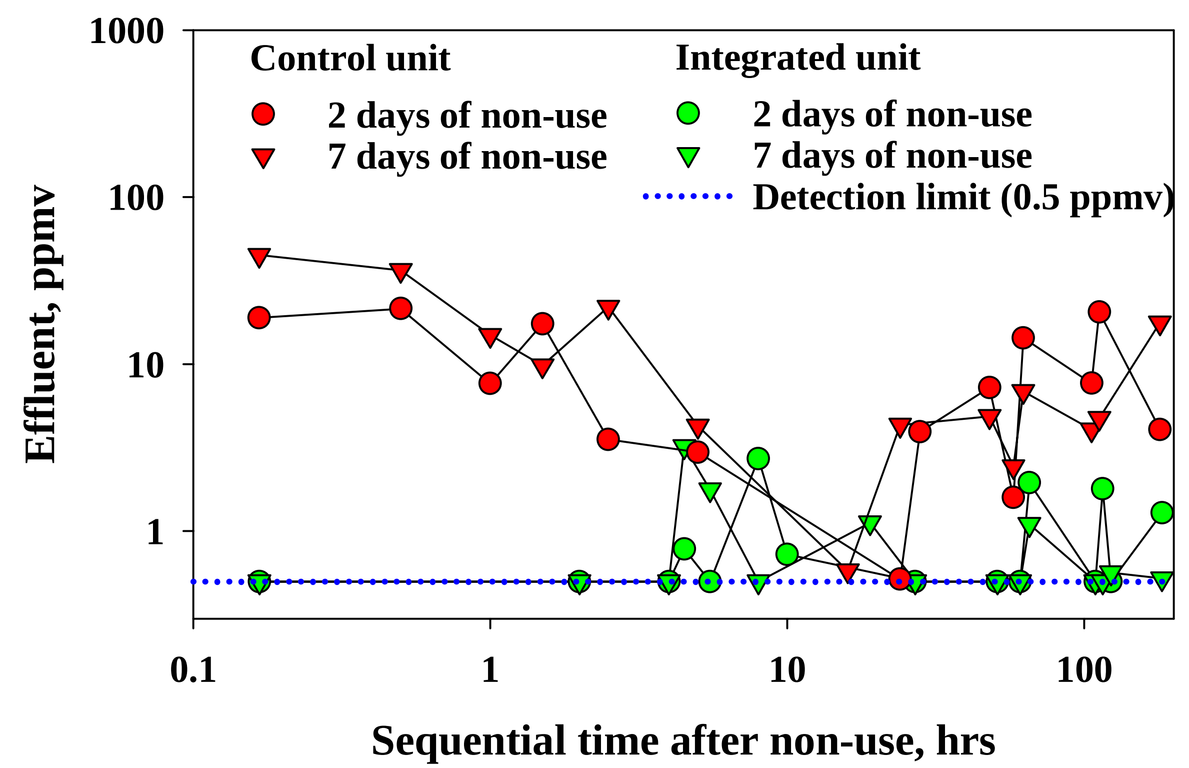


Phase III: Integrated Treatment Scheme

- **Results: Effluent performance after Non-use period**

Phase III: Integrated Treatment Scheme

- Results: Effluent performance after Non-use period



Phase III: Integrated Treatment Scheme

- **Results: Further Application**

Phase III: Integrated Treatment Scheme

- **Results: Further Application**

4-different feeding condition

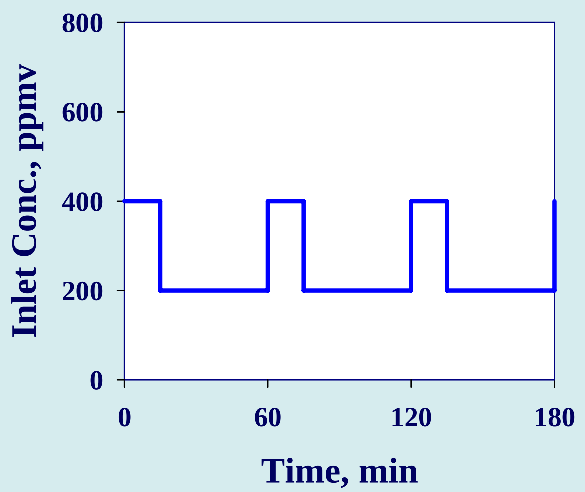
- 8-hr average effluent
- 1st order kinetic constants : Estimate of biological activity

Phase III: Integrated Treatment Scheme

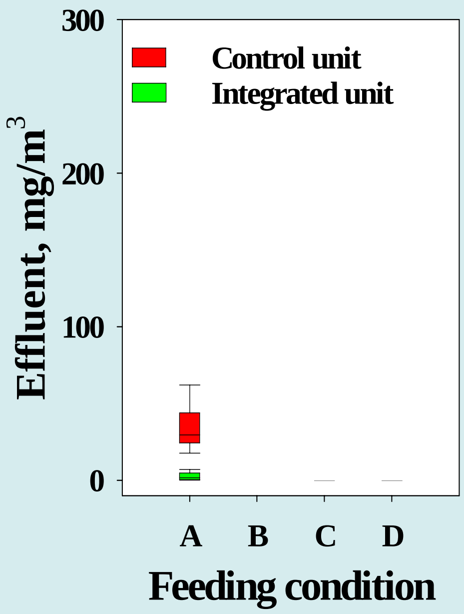
- Results: Further Application

Feeding Condition

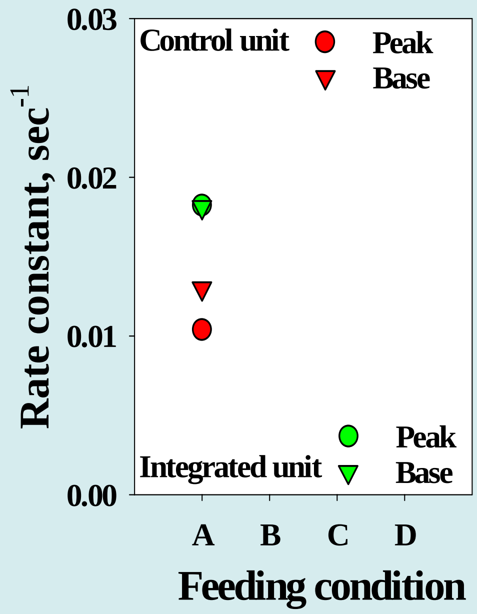
- Type A : 46.9 g/m³·hr



a)8-hr average effluent



b) Reaction rate constant

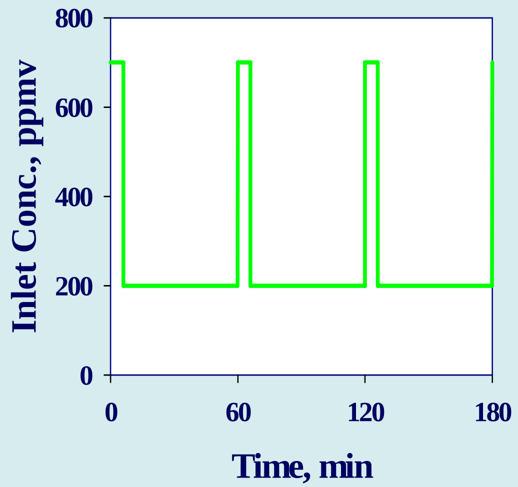


Phase III: Integrated Treatment Scheme

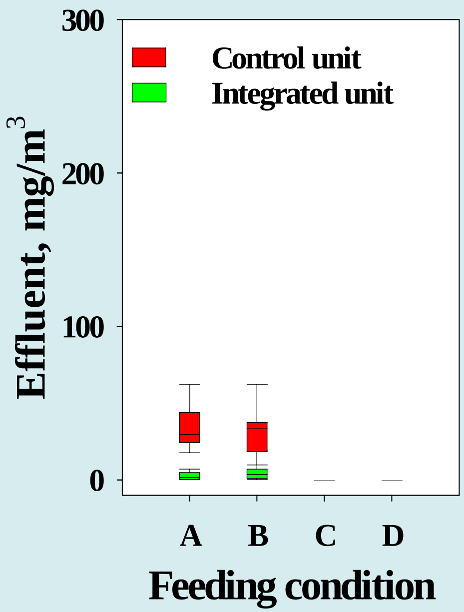
- **Results: Further Application**

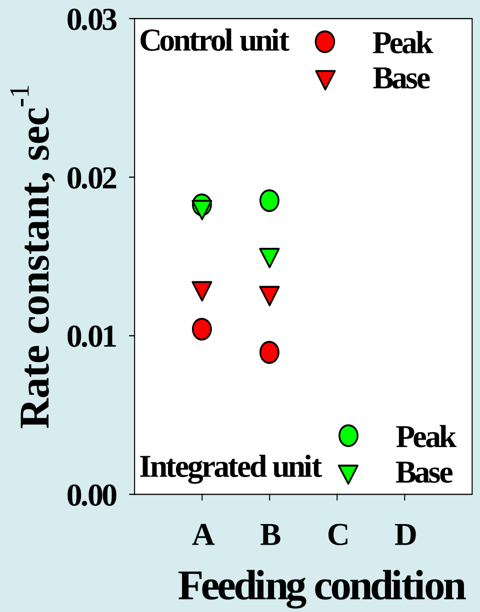
Feeding Condition

- Type B : 46.9 g/m³·hr (High Peak)



a)8-hr average effluent **b) Reaction rate constant**



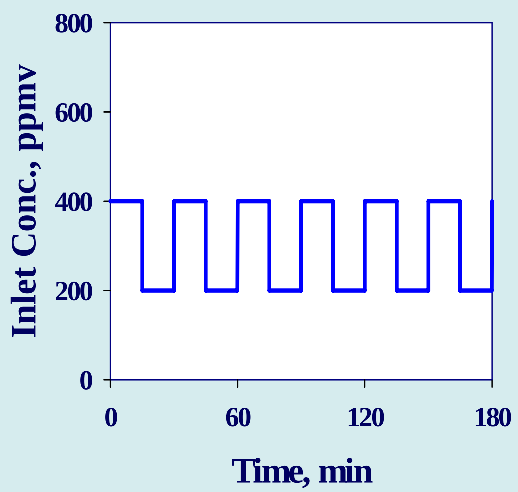


Phase III: Integrated Treatment Scheme

- Results: Further Application

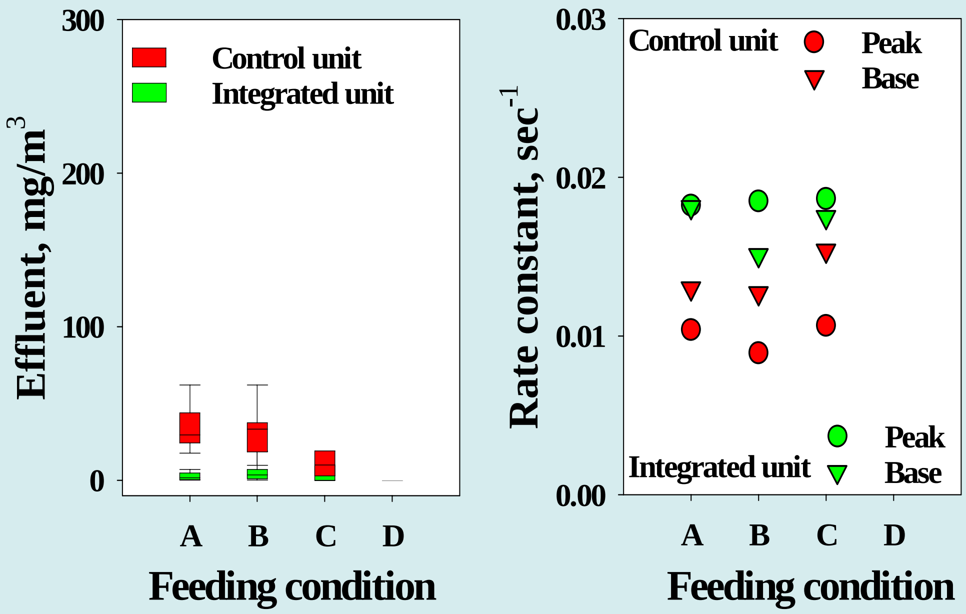
Feeding Condition

- Type C : 56.3 g/m³·hr (Frequent Peak)



a)8-hr average effluent

b) Reaction rate constant

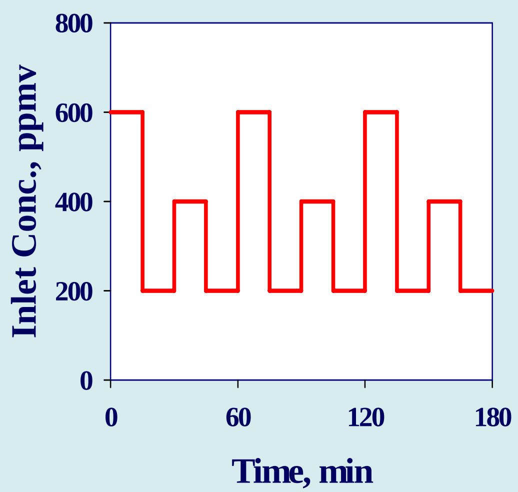


Phase III: Integrated Treatment Scheme

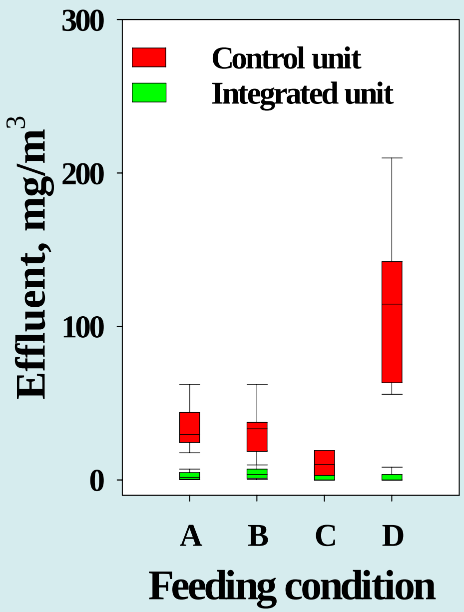
- **Results: Further Application**

Feeding Condition

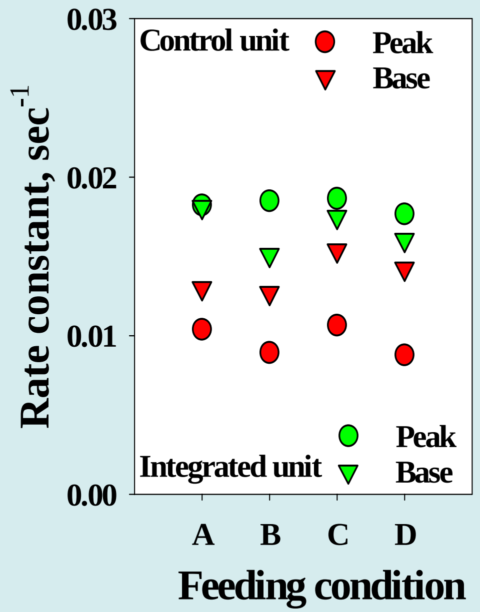
- Type D : 65.9 g/m³·hr
  (High & Frequent Peak)



a)8-hr average effluent



b) Reaction rate constant



Phase III: Integrated Treatment Scheme

- **Results: Comparison of reactor volume**

Reactor volume of a single biofilter to achieve the same treatment goal as in the integrated system

Phase III: Integrated Treatment Scheme

- **Results: Further Application**

Reactor volume of a single biofilter to achieve the same treatment goal as in the integrated system

Feeding Condition	Type A	Type B	Type C	Type D
Peak concentration ($C_{i,p}$), ppmv	400	700	400	600
(g/m^3)	(1.53)	(2.68)	(1.53)	(2.30)
Biofilter bed volume required (V), m^3 **	0.00435	0.00761	0.00435	0.00653
$V / V_{integrated}$ **	1.5	2.6	1.5	2.2

* Volume of the integrated unit = 0.00293 m^3

Phase III: Integrated Treatment Scheme

- **Conclusion**

The net effect of the 2-bed adsorption was VOC concentration stabilization that makes it amenable for effective stable biodegradation

1. The 2-step cycle in the adsorption unit successfully performed particular functions as
    - A polishing unit to abate the initial acclimation for the biofilter;
    - A buffering unit to mitigate the biofilter performance;
    - A feeding source for the biofilter without any feeding phase
2. Details of the reactor volume suggest that capital expense can be minimized by achieving a careful design and operation of the integrated treatment scheme.

Acknowledgements

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Development of Integrated Treatment Scheme of Adsorption and Biofilter for VOC Removal

Dissertation Defense for the Degree of Ph.D.