Advanced treatment of low-strength wastewater using SBR and vertical-type MBRs

Dr. Hang-Sik Shin

Dept. of Civil and Environmental Engineering,
Korea Advanced Institute of Science and Technology (KAIST),
South Korea

Characteristics of sewage in Korea

[Unit: mg/L]

Category	Year 2000				
	BOD_5	COD_{Mn}	SS	T-N	T-P
Designed value	143.8	-	152.5	-	-
Influent	102.4	62.0	110.7	33.9	2.9
Ratio (%)	71.2	-	72.6	-	-

Low C/N ratio → insufficient for nutrient removal

Removal efficiencies of organic and nutrients

Year 2000	Category				
	BOD_5	COD_{Mn}	SS	T-N	T-P
Influent (mg/L)	102.4	62.0	110.7	33.9	2.9
Effluent (mg/L)	11.7	13.3	8.4	21.1	1.2
Removal (%)	88.6	78.6	92.4	37.4	57.4

Low nutrient removal efficiency !!!

Effluent standards for sewage treatment plants

[Unit: mg/L except *E. coli*.]

<table>
<tr><th rowspan="2">Area</th><th colspan="3">Before 2002</th><th colspan="4">After 2002</th></tr>
<tr><th>BOD_5
SS</th><th>T-N</th><th>T-P</th><th>BOD_5
SS</th><th>T-N</th><th>T-P</th><th>E. coli.
(CFU/mL)</th></tr>
<tr><td>Special</td><td rowspan="2">20</td><td rowspan="2">60</td><td rowspan="2">8</td><td>10</td><td>20</td><td>2</td><td>3,000</td></tr>
<tr><td>Other</td><td>20</td><td>60</td><td>8</td><td>3,000</td></tr>
</table>

CHARACTERISTICS OF MEMBRANE FOULING AND NUTRIENT REMOVAL IN A VERTICAL-TYPE MEMBRANE BIOREACTOR

Part 1: Development of operating factors

Municipal wastewater
low C/N ratio

Operating factors

Internal recycle rate
HRT
C/N ratio

<Novel vertical-type MBR>
Compact system
Organic, N, P removal

Fouling

Physical/
Chemical/
Biological factors

Performance

SS, organics
Nutrients
E. coli

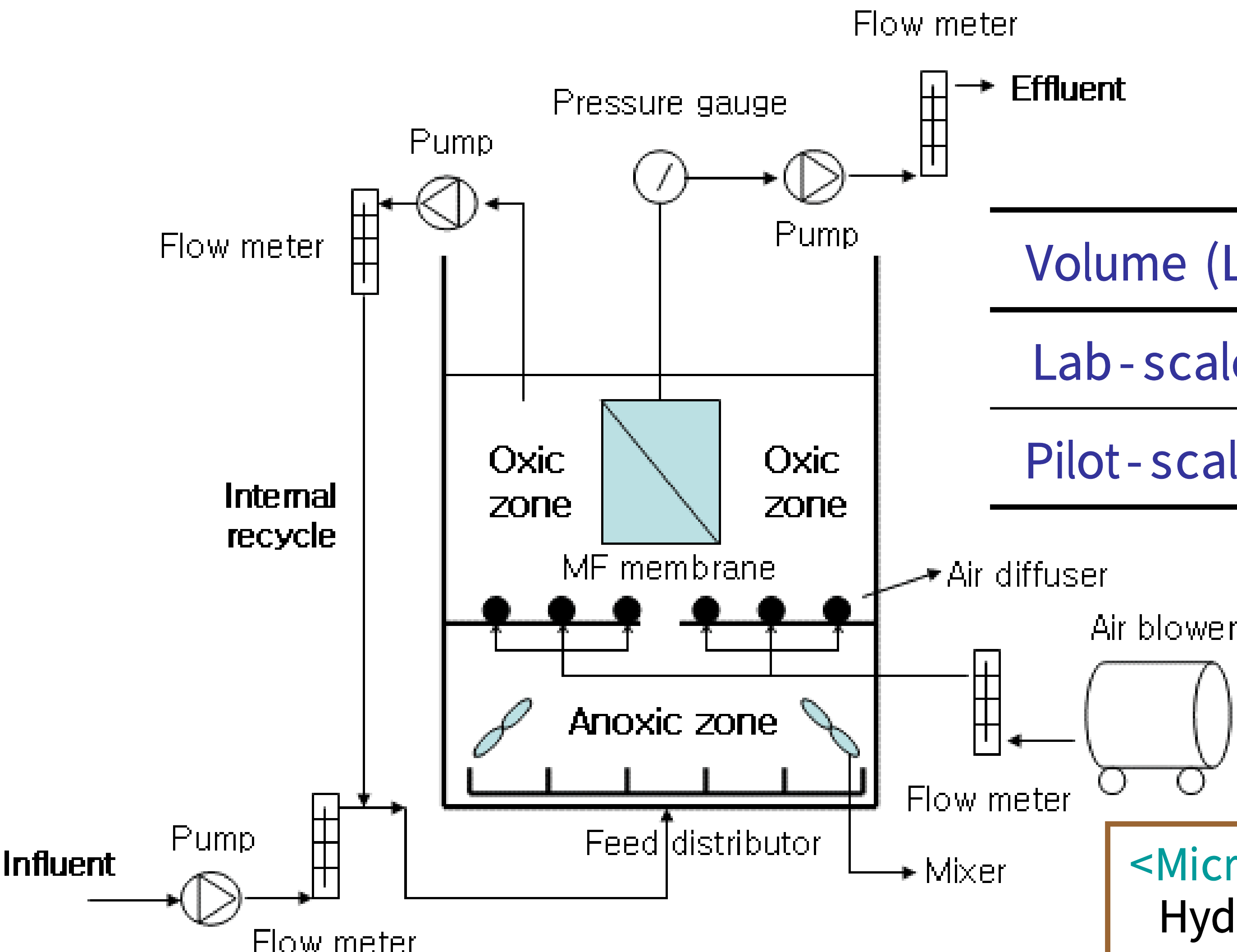
Kinetics and
EBPR metabolism

μ_{max}, k_d, K_s, Y
PHAs, poly-P,
glycogen

Population
dynamics

PCR-DGGE

Vertical-type membrane bioreactor



Volume (L)	Ax	Ox
Lab-scale	12	20
Pilot-scale	500	840

<Microfiltration membrane>
Hydrophilic polyethylene
Hollow fiber module
Pore size = 0.4μm

Summary of results; Lab-scale study

Characteristics of synthetic wastewater

Constituents	Chemical formula	Concentration
COD	$C_6H_{12}O_6$	120-300 mg/L
T-N	$(NH_4)_2SO_4$	30 mg/L
T-P	KH_2PO_4	6 mg/L
Alkalinity	$NaHCO_3$	200 mg/L
Trace metals and yeast extract		

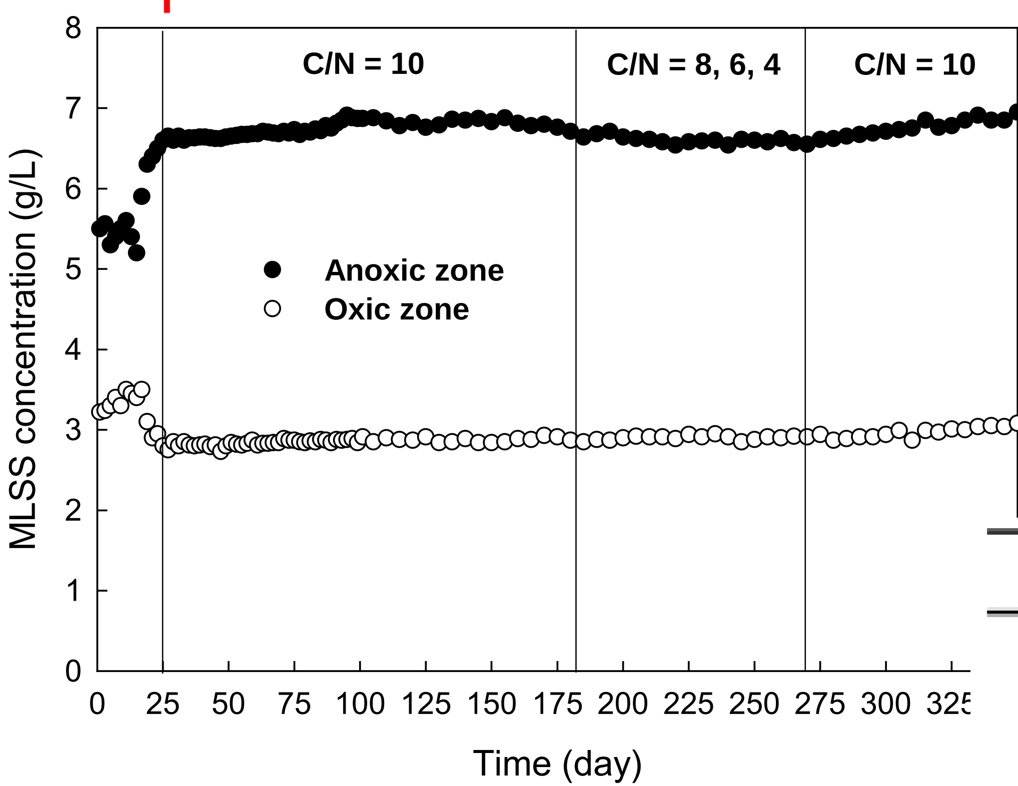
Experimental conditions

- SRT = 30 days

Phase	Internal recycle rate	TCOD/T-N ratio	HRT	Operation period
1	**3Q**	10	12 hrs	1-120 days
2	**4Q**			121-150 days
3	**5Q**			151-180 days
4	4Q	**8**	12 hrs	181-210 days
5		**6**		211- 240 days
6		**4**		241-270 days
7	4Q	10	**10 hrs**	271-300 days
8			**8 hrs**	301-330 days
9			**6 hrs**	331-360 days

Sludge production in vertical-type MBR

MLSS = 6.7 g/L (Ax), 2.7 g/L (Ox)



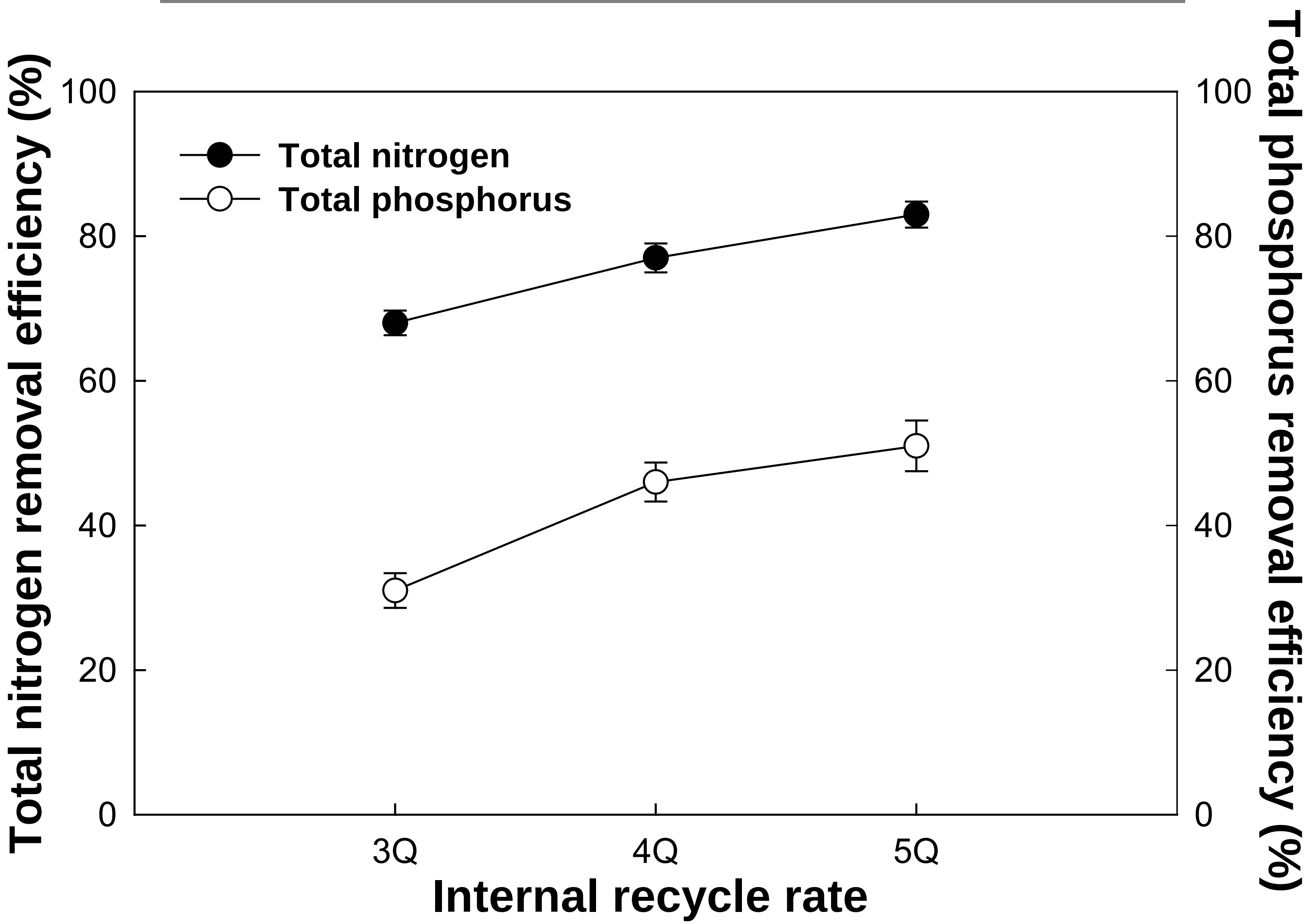
<C/N ratio = 10>
- Wasted sludge = 3.1 g/day
- Removed organic = 12.1 g/day

<Sludge production>
= 0.25 g TS/g COD removed

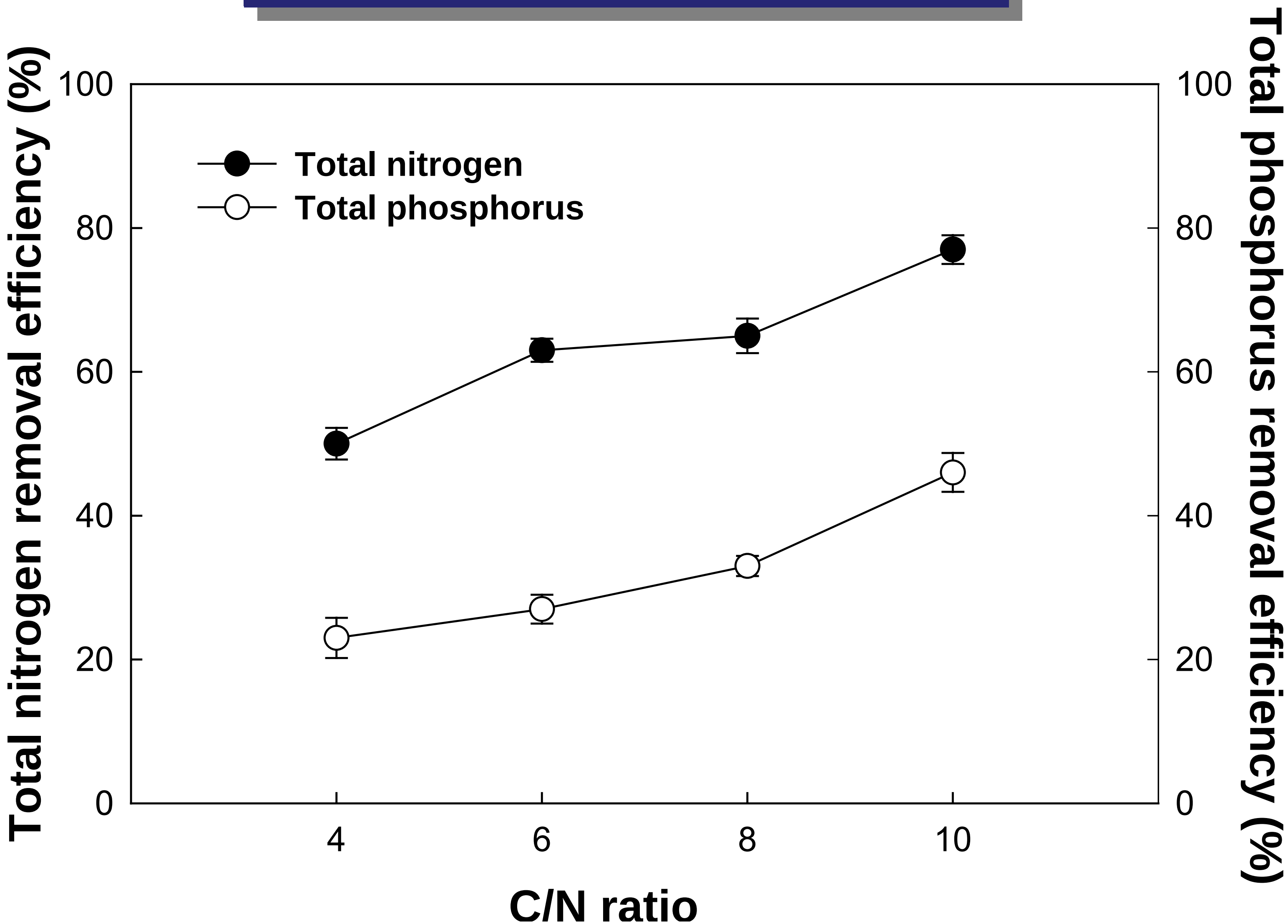
Treatment process	Sludge production (g TS/g BOD)
Submerged MBR	0.01-0.30
Biological aerated filter	0.15-0.25
Tricking filter	0.30-0.50
Conventional activated sludge	0.60
Granular media BAF	0.63-1.06

[Source: Mayhew *et al*., 1997]

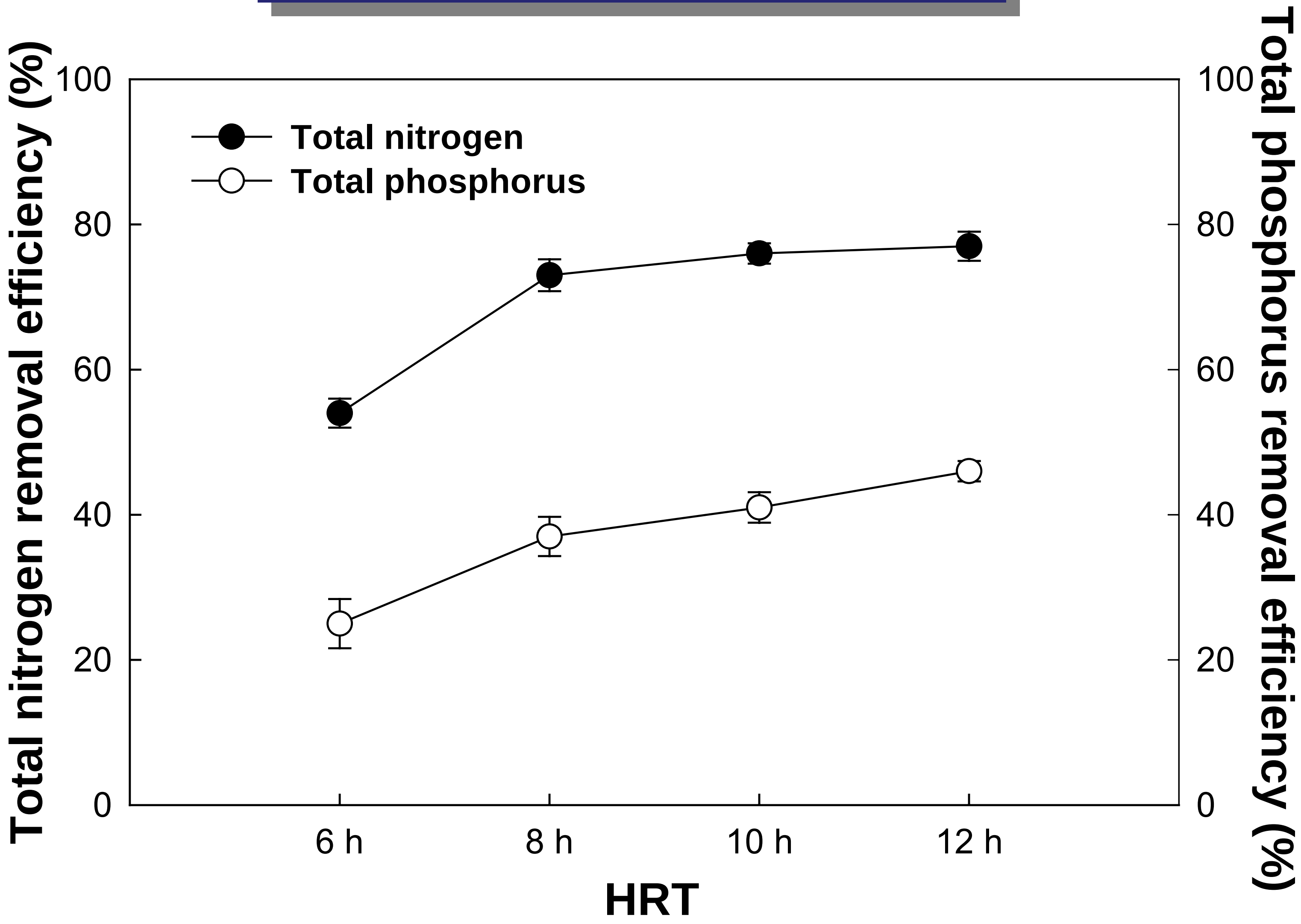
Effect of internal recycle rate



Effect of C/N ratio



Effect of HRT



Summary of results; Pilot-scale study

Characteristics of influent and external carbon source

Food waste → External carbon source ← WWTP sludge

Constituents		Sewage	External carbon source
CODcr	Total	226 ± 36	14,800 ± 1,200
(mg/l)	Soluble	161 ± 25	2,300 ± 580
SS	Total	153 ± 60	1,560 ± 136
(mg/l)	Volatile	107 ± 35	880 ± 76
Nitrogen	TKN	41 ± 10	783 ± 26
(mg/l)	NH_4-N	28 ± 5	579 ± 18
Phosphorus	Total	3.0 ± 0.6	186 ± 36
(mg/l)	Soluble	1.9 ± 0.3	115 ± 14
TVFAs as COD (mg/l)		-	1,410 ± 236
pH		7.3 ± 0.2	4.5 ± 0.1

TVFAs = lactate(2%) + acetate(25%) + propionate(12%) + butyrate(18%) + valerate(35%) + caporate(8%)

Pilot-scale vertical-type MBR

Auto control

Vertical-type MBR

	Anoxic	Oxic
MLSS (g/L)	8.68	4.21
ORP (mV)	-112	+213

Effluent

Experimental conditions

- SRT = 60 days
- Internal recycle = 3Q

Run	Control	Operation period
1	HRT = 10 hrs	1-68 days
2	HRT = 8 hrs	69-100 days
3	HRT = 6 hrs	101-130 days
4	HRT = 4 hrs	131-160 days
5	HRT = 8 hrs, Chemical coagulation ($FeCl_3$)	161-190 days
6	HRT = 8 hrs, external carbon addition (0.43%, v/v)	191-210 days
7	HRT = 8 hrs, external carbon addition (0.86%, v/v)	221-250 days

Organic and nutrient removal efficiencies

Run	TCOD In (mg/l)	TCOD Out (mg/l)	TCOD Removal (%)	T-N In (mg/l)	T-N Out (mg/l)	T-N Removal (%)	T-P In (mg/l)	T-P Out (mg/l)	T-P Removal (%)
2	203	18	91	39	16	59	2.4	1.6	35
3	227	15	93	42	19	55	2.7	1.9	30
4	231	14	93	41	23	44	2.6	1.8	32
5	219	8	96	41	16	61	2.9	0.5	**83**
6	223	9	96	43	12	**72**	3.1	1.5	**52**
7	220	13	94	43	11	**75**	3.0	1.0	**67**

☞ **Run 2 – 4; HRT decrease → nutrient removal efficiency decrease**

☞ **Run 5; coagulation with ferric chloride; phosphorus removal 32% → 83%**

☞ **Run 6, 7; addition of external carbon → increase of nutrient removal efficiency (Nitrogen: 44% → 75%, Phosphorus: 32% → 67%)**

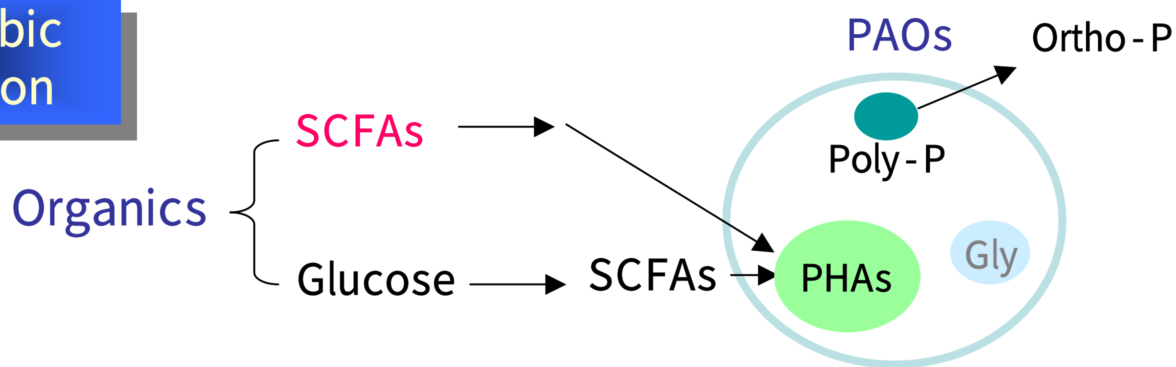
Reuse of effluent in vertical-type MBR

Parameter	Criteria/Guideline			Effluent quality
	Toilet flushing	**Pond/ Fountain**	**Cleaning water**	
Total coli form (CFU/mL)	ND	ND	ND	ND
Suspended solid (mg/L)	-	-	-	0
Residual chlorine (mg/L)	>0.2	>0.2	>0.2	18 (Cl^-)
Turbidity (NTU)	<2	<2	<2	<0.2
Odor/Smell	desirable	desirable	desirable	desirable
pH	5.8-8.5	5.8-8.5	5.8-8.5	7.5
COD_{Mn} (mg/L)	<20	<20	<20	1.5
T-N (mg/L)	-	-	-	<20
T-P (mg/L)	-	-	-	<2.0

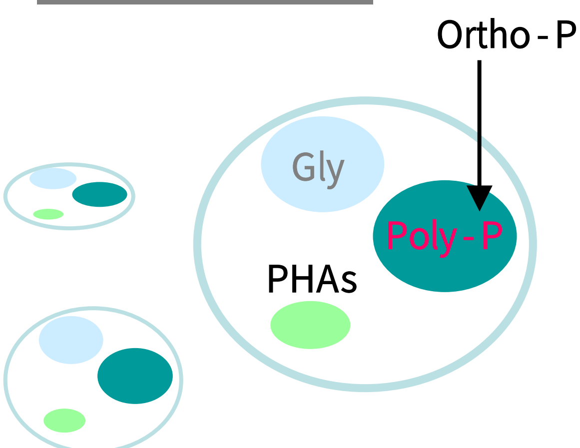
[ND = not detected]

Enhanced Biological Phosphorus Removal

Anaerobic condition



Aerobic condition

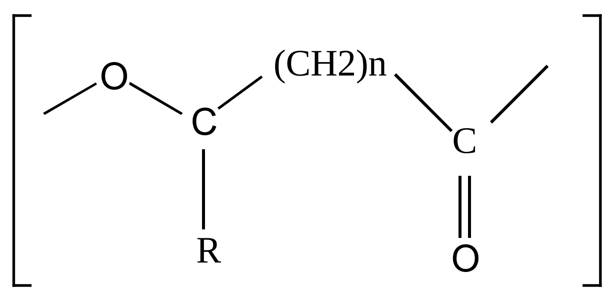


- PHAs (poly - hydroxyalkanoates) ?

  : water - insoluble polyesters of alkanoic acids

  ➔ Biodegradable polymer

- General structural formula of PHAs



100-30,000

Carbon source

Acetate
Glucose
Complex organics

Accumulated PHAs

3HB
3HV+3HB or copolymer
??

Compositions of PHAs in this study

Poly-3-hydroxybutyrate (3HB) = 11% (C4)
Poly-3-hydroxyvalerate (3HV) = 67% (C5)

Short chain length PHAs

Poly-3-hydroxyhexanoate (3HH) = 10% (C6)
Poly-3-hydroxyoctanote (3HO) = 8% (C8)
Poly-3-hydroxydecanoate (3HD) = 3% (C10)
Poly-3-hydroxydodecanoate (3HDD) = 1% (C12)

Medium chain length PHAs

PHAs accumulation pathways

Group 1; ***Ralstonia eutropha*** **(*Alcaligenes eutrophus*)**

Acetyl-CoA → three steps → 3HB

Group 2; **Photosynthetic bacterium (*Rhodospirillium rubrum*)**

Acetyl-CoA → five steps → 3HB

Group 3; **Most *pseudomonas* (*Pseudomonas oleovorans*)**

Intermediates from the b-oxidation → MCL-PHA

Group 4; **Almost *pseudomonas* (*Pseudomonas aeruginosa*)**

Acetyl-CoA → many steps → MCL-PHA

[Source: *Biomaterials*, Macmillan Publishers Ltd., 1991]

Part 1: conclusions

Lab-scale study

- Vertical-type MBR → reduce sludge production (about 40% of conventional activated sludge process)
- High removal efficiencies of organics (> 95%) and SS (100%) were maintained
- IR (3Q → 4Q → 5Q); T-N= 68% → 83%, T-P= 31% → 51%
- COD/T-N ratio (4 → 10); T-N= 50% → 80%, T-P= 23% → 46%
- HRT (6 hrs → 12 hrs); T-N= 54% → 79%, T-P= 25% → 46%
- Desirable operating conditions (for 80% nitrogen removal);
  IR ≥ 4Q, C/N ≥ 10, HRT ≥ 8 hrs

Pilot-scale study

- Phosphorus removal was restricted at long SRT of 60 days
- Effluent quality at HRT of 8 hrs, internal recycle rate = 300%
  COD_{cr} < 18 mg/L, T-N < 20 mg/L, T-P < 2 mg/L
- Addition of coagulant (ferric chloride);
  T-P removal efficiency increased 35% → 83%
- With external carbon source (food waste + sludge);
  - nitrogen and phosphorus removal efficiencies were improved from 59% and 35% to 75% and 67%, respectively.
  - Several kinds of PHAs were observed in biomass
    PHAs = 3HB (11%) + 3HV (67%) + 3HH (10%) + 3HO (8%) + 3HD (3%) + 3HDD (1%)

Part 2: Characteristics of membrane fouling

Municipal wastewater (Low C/N ratio)

<Novel system>

Vertical-type MBR
Anoxic + Oxic zone

Operating factors
- Internal recycle rate
- HRT
- C/N ratio

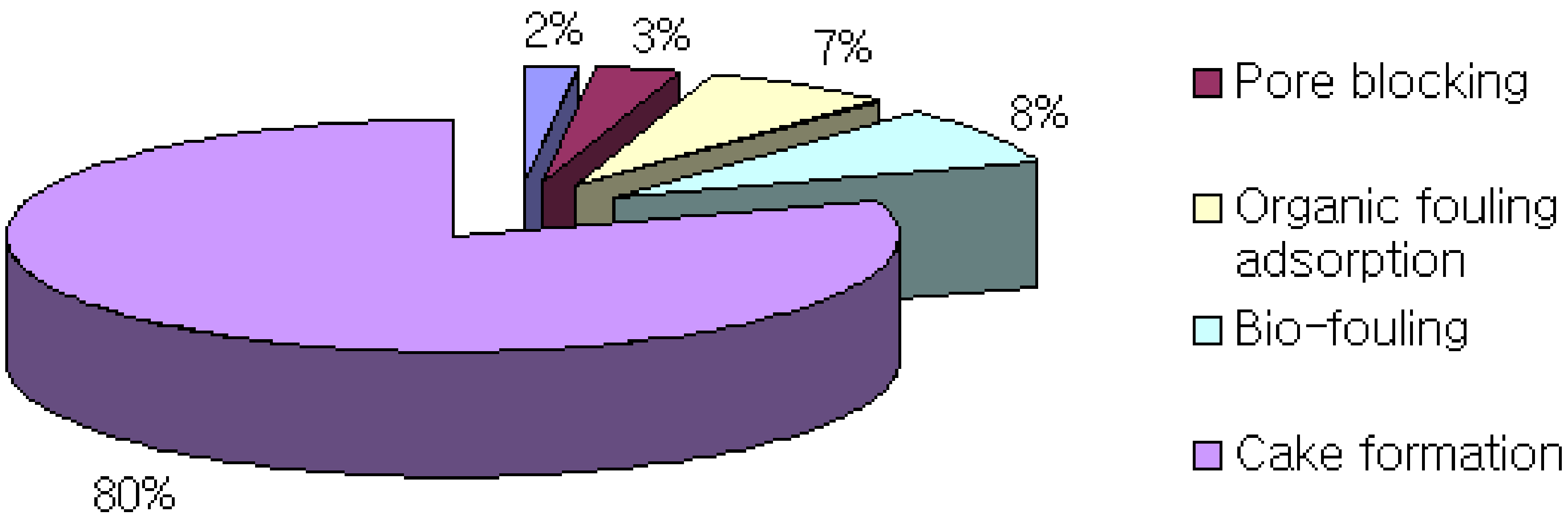
Fouling
- Physical/
- Chemical/
- Biological factors

Performance
- SS, organics
- Nutrients
- *E. coli*

Kinetics and EBPR metabolism
- μ_{max}, k_d, K_s, Y
- PHAs, poly-P, glycogen

Population dynamics
- PCR-DGGE

Fouling factors in the MBRs treating sewage



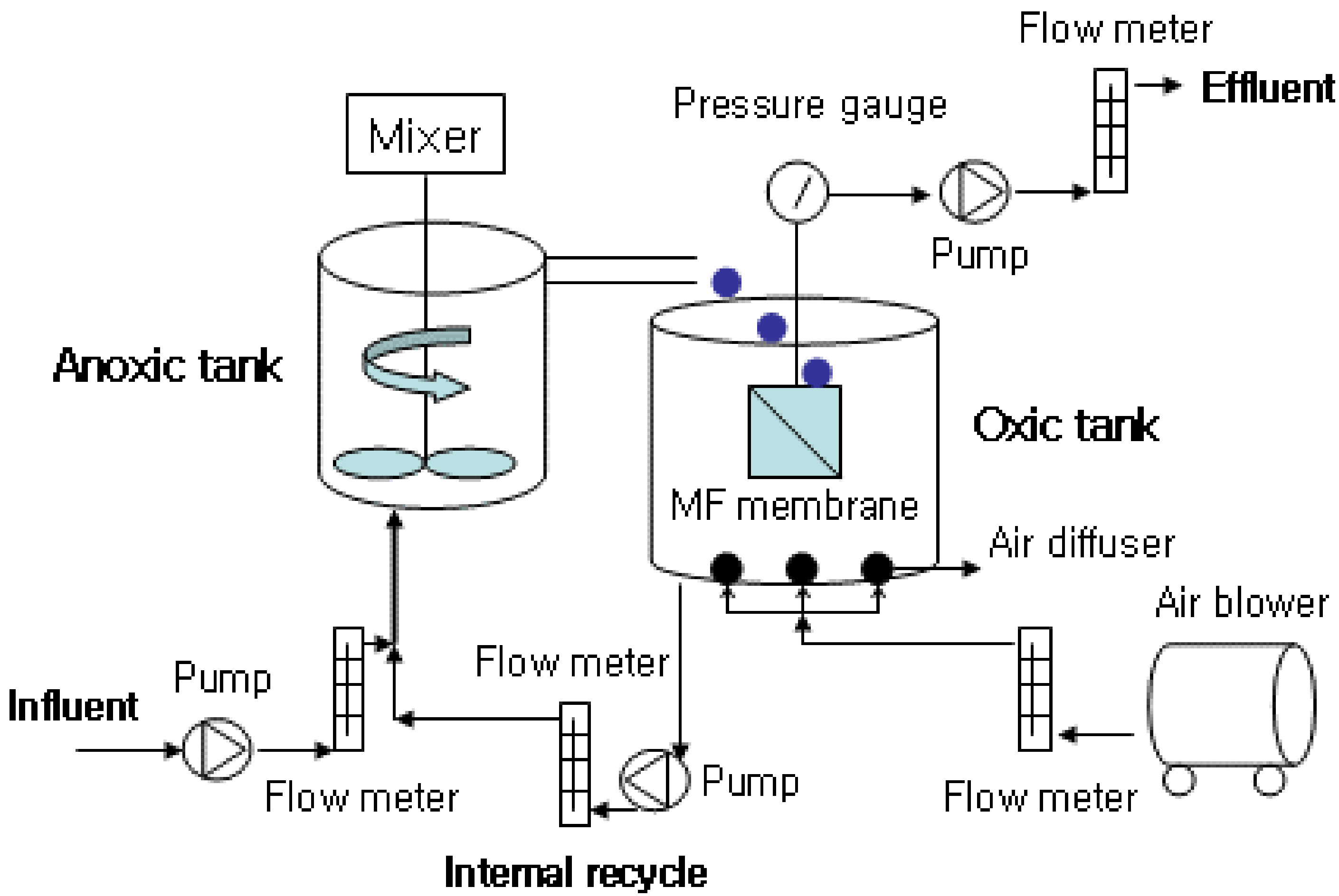
[Source: STOWA, 2001]

Desirable operating conditions to reduce fouling

- Constant flux or constant pressure → constant flux at subcritical flux (Defrance *et al*., 1999)
- Intermittent suction (Hong *et al*., 2002)
- Fouling: side stream MBR> submerged MBR (Cote *et al*., 1997)
- Proper biomass concentration (Defrance *et al*., 1999)
- Minimize the interfiber clogging (Futamura *et al*., 1994)

Comparison of fouling; vertical vs. AO MBR

Anoxic-Oxic (AO) MBR



Experimental conditions

Lab-scale	Vertical MBR		AO MBR	
	AX	OX	AX	OX
SRT	30 days			
HRT (hrs)	3	5	3	5
Filtration flux	6.2 L/m^2/hr (40 L/d) On (8 min) + Off (2 min)			
Internal recycle	300%			
MLSS (g/L)	6.7	2.7	4.3	4.6
ORP (mV)	-47	+257	-63	+314

Characteristics of synthetic wastewater

Constituents	Chemical formula	Concentration
COD	$C_6H_{12}O_6$	300 mg/L
Nitrogen	$(NH_4)_2SO_4$	30 mg/L
Phosphorus	KH_2PO_4	6 mg/L
Alkalinity	$NaHCO_3$	200 mg/L
Trace metals and yeast extract		

Analytical methods

Membrane resistance: UF membrane (YM30) + Amicon cell unit

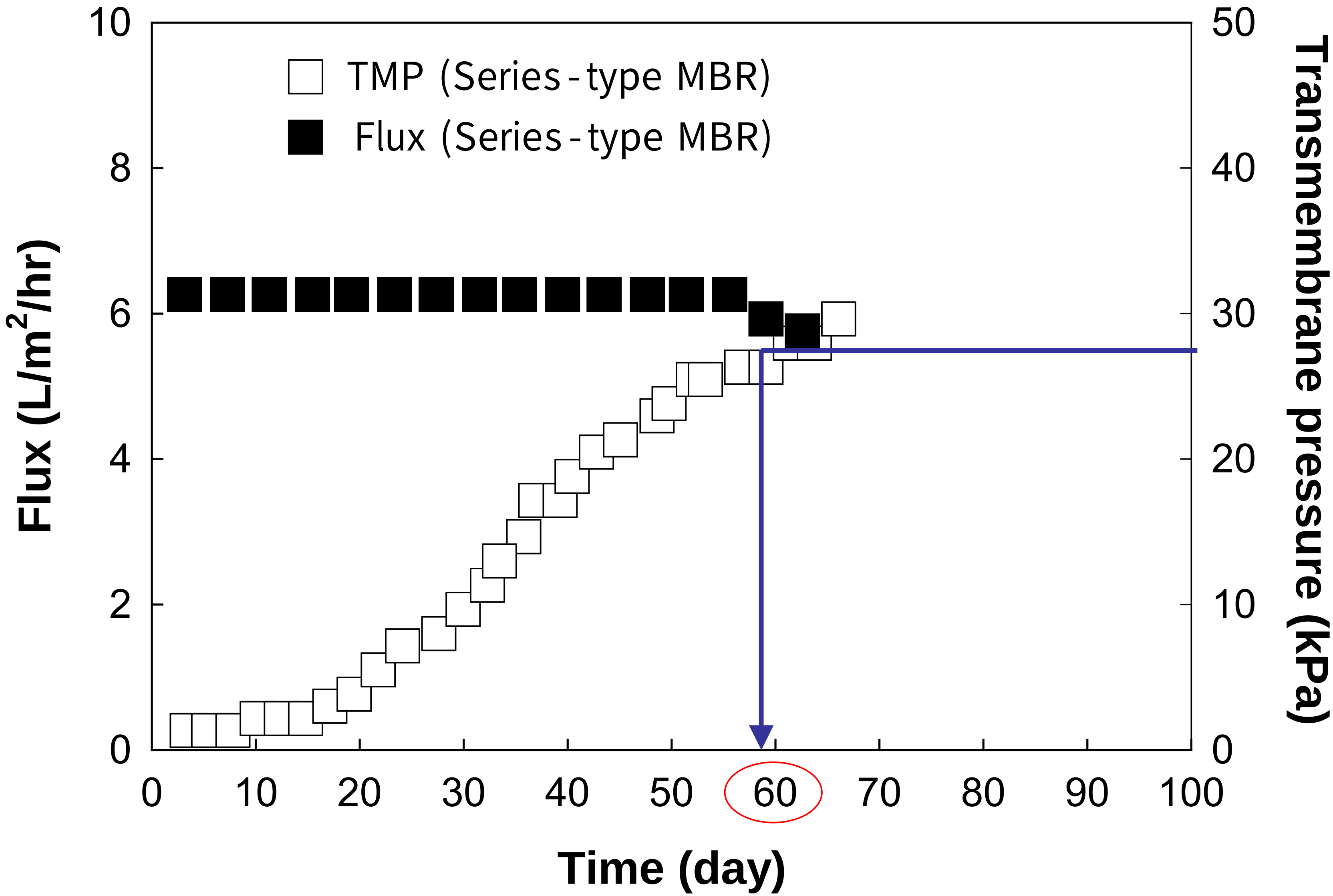
Particle size distribution: Particle size analyzer (PSS, USA, 0.5 – 500 μm)

Hydrophobicity: Specific UltraViolet Absorbance (= UV_{254}/DOC, Edzwald *et al.*, 1985)

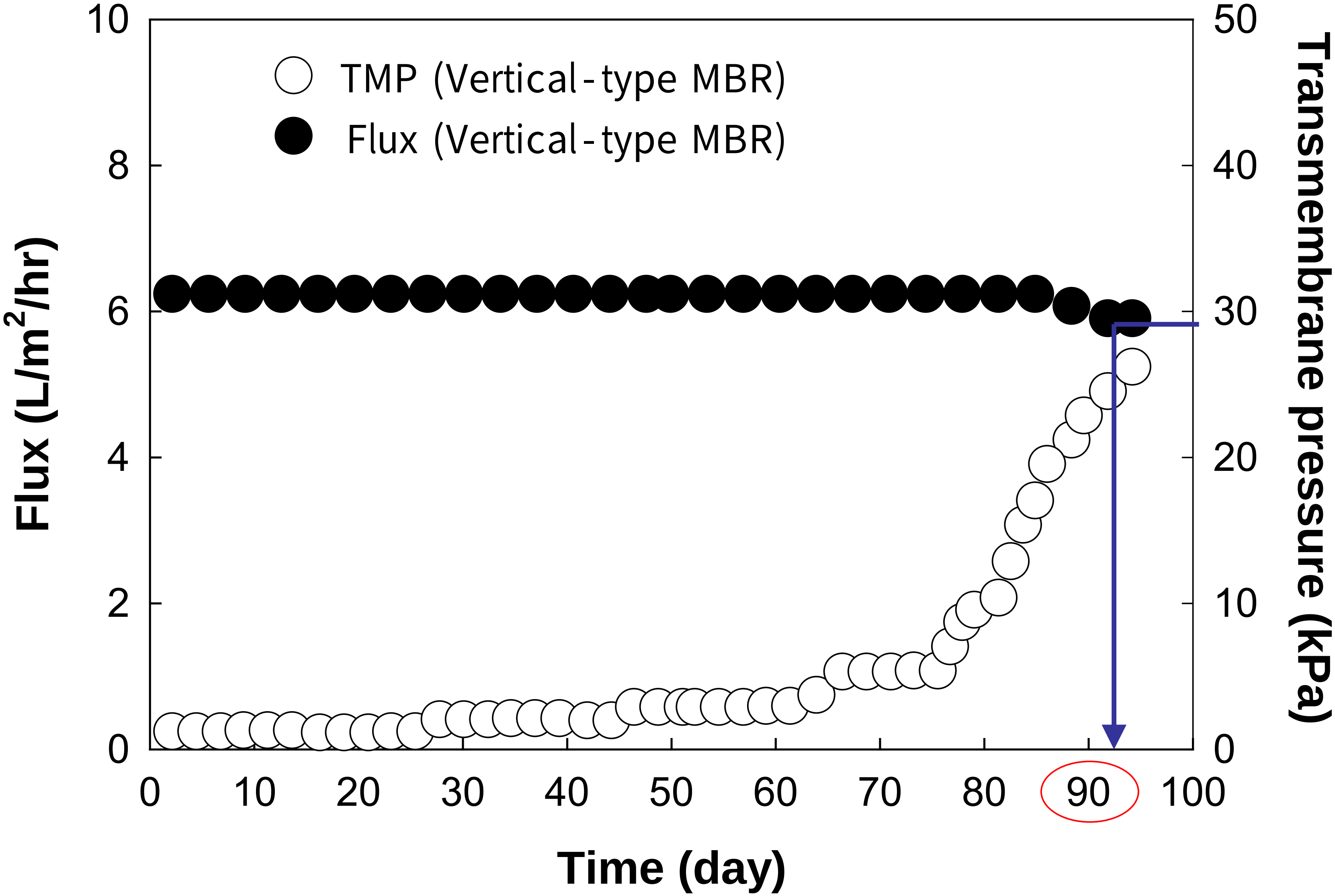
Viscosity: Cannon-Fenske Viscometer (Cannon Instrument Company., USA)

Extracellular Polymeric Substances: carbohydrate and protein compounds
→ Heat extraction method (Brown, 1980)

Variation of flux and TMP; AO MBR



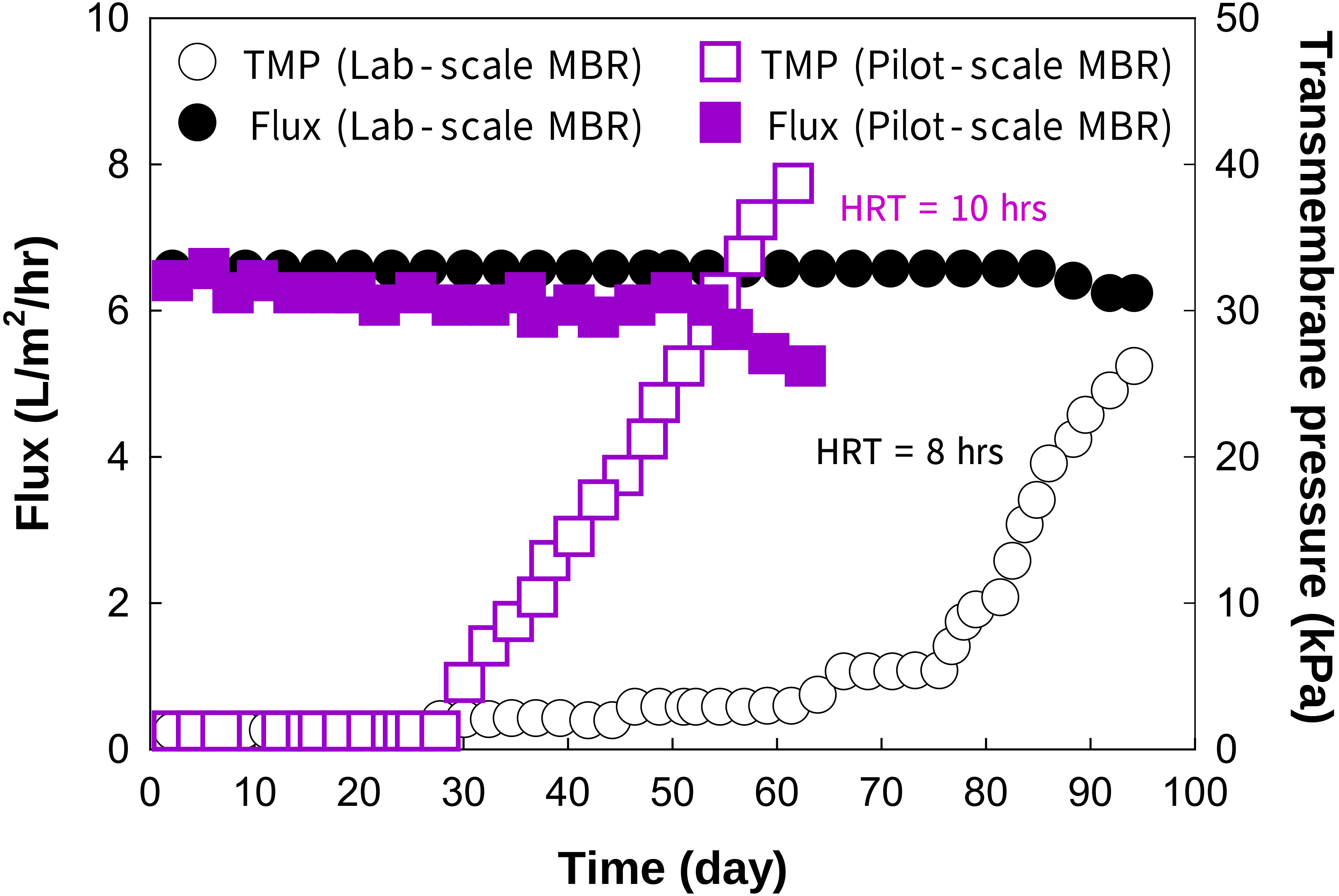
Variation of flux and TMP; vertical-type MBR



Factors affecting membrane fouling

MBR type		Vertical	AO
Particle size (vol. wt. mean)		92.5 μm	98.4 μm
Hydrophobicity		0.022 $m^{-1}mg^{-1}L$	0.024 $m^{-1}mg^{-1}L$
EPSc		34.2 mg/g VSS	48.4 mg/g VSS
EPSp		32.8 mg/g VSS	35.1 mg/g VSS
Viscosity		1.20 mm^2/s	1.22 mm^2/s
Membrane resistance	Total	$3.6 \times 10^{12}\ m^{-1}$	$4.4 \times 10^{12}\ m^{-1}$
	Rm	$0.2 \times 10^{12}\ m^{-1}$	$0.2 \times 10^{12}\ m^{-1}$
	Ra + Rp	$1.4 \times 10^{12}\ m^{-1}$	$1.3 \times 10^{12}\ m^{-1}$
	Rc	$2.0 \times 10^{12}\ m^{-1}$	$2.9 \times 10^{12}\ m^{-1}$

Comparison; lab vs. pilot-scale MBR



Factors affecting membrane fouling

Vertical-type MBR		Lab-scale	Pilot-scale
Particle size (vol. wt. mean)		92.5 μm	55.6 μm
Hydrophobicity		0.022 $m^{-1}mg^{-1}L$	0.019 $m^{-1}mg^{-1}L$
EPSc		34.2 mg/g VSS	74.9 mg/g VSS
EPSp		32.8 mg/g VSS	35.6 mg/g VSS
Viscosity		1.20 mm^2/s	1.31 mm^2/s
Membrane resistance	Total	$3.6 \times 10^{12}\ m^{-1}$	$13.5 \times 10^{12}\ m^{-1}$
	Rm	$0.2 \times 10^{12}\ m^{-1}$	$0.2 \times 10^{12}\ m^{-1}$
	Ra + Rp	$1.4 \times 10^{12}\ m^{-1}$	$3.9 \times 10^{12}\ m^{-1}$
	Rc	$2.0 \times 10^{12}\ m^{-1}$	$9.4 \times 10^{12}\ m^{-1}$

Membrane resistance in vertical-type MBR

Run	Operating condition		Resistance (x 10^{12} m^{-1})			
			Rm	Rp	Rc	**Rt**
1	**HRT 10 hrs**		0.2	2.2	4.9	**7.3**
2	**HRT 8 hrs**		0.2	3.9	9.4	**13.5**
3	**HRT 6 hrs**		0.3	8.9	20.5	**29.7**
4	**HRT 4 hrs**		0.2	10.1	38.1	**48.4**
5	HRT 8 hrs	**$FeCl_3$**	0.2	3.2	13.3	**16.7**
6		**E.C. 0.43%**	0.2	3.4	18.1	**21.7**
7		**E.C. 0.86%**	0.3	3.8	21.1	**25.5**

Membrane fouling in a pilot-scale MBR

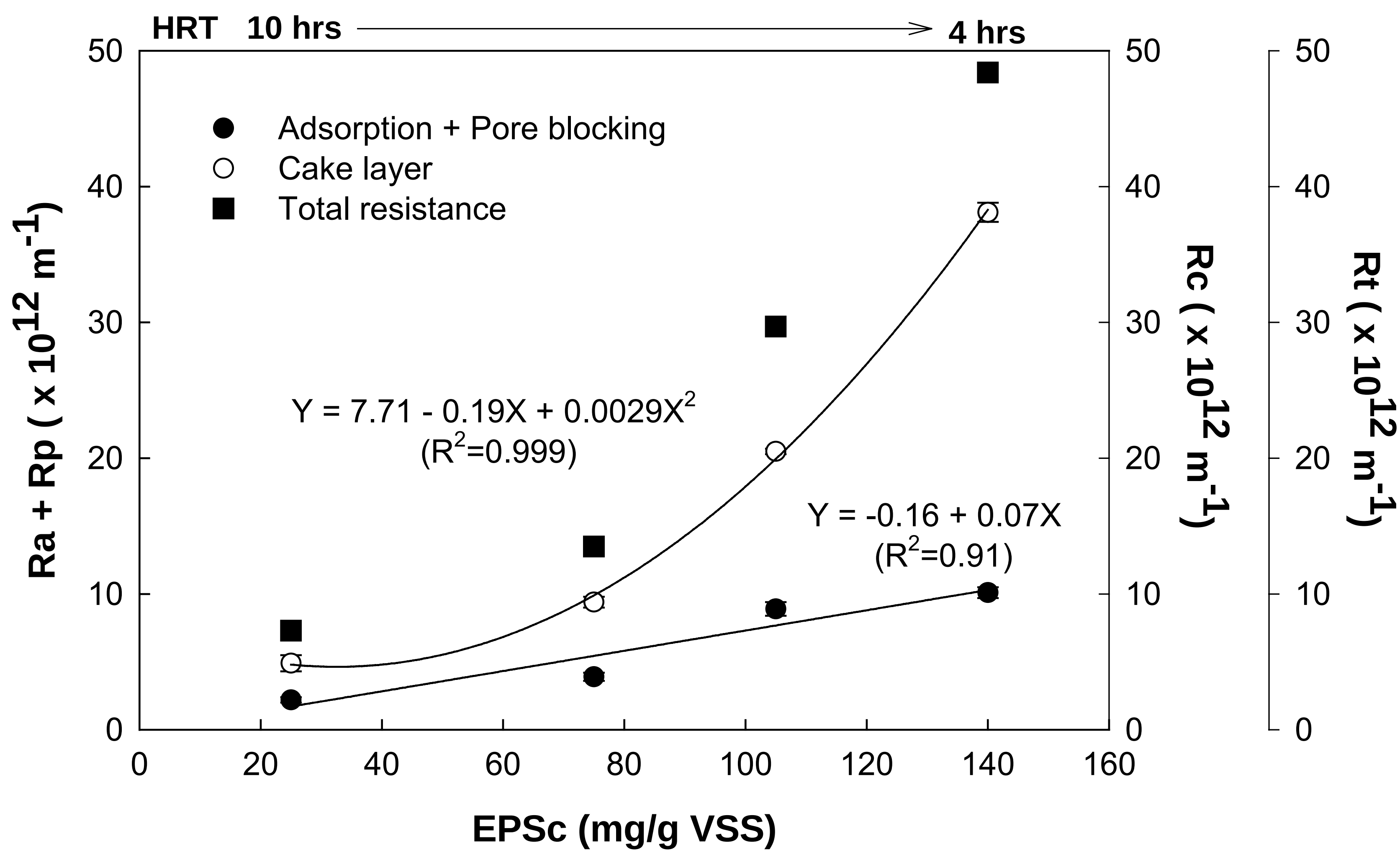
Before use

After use

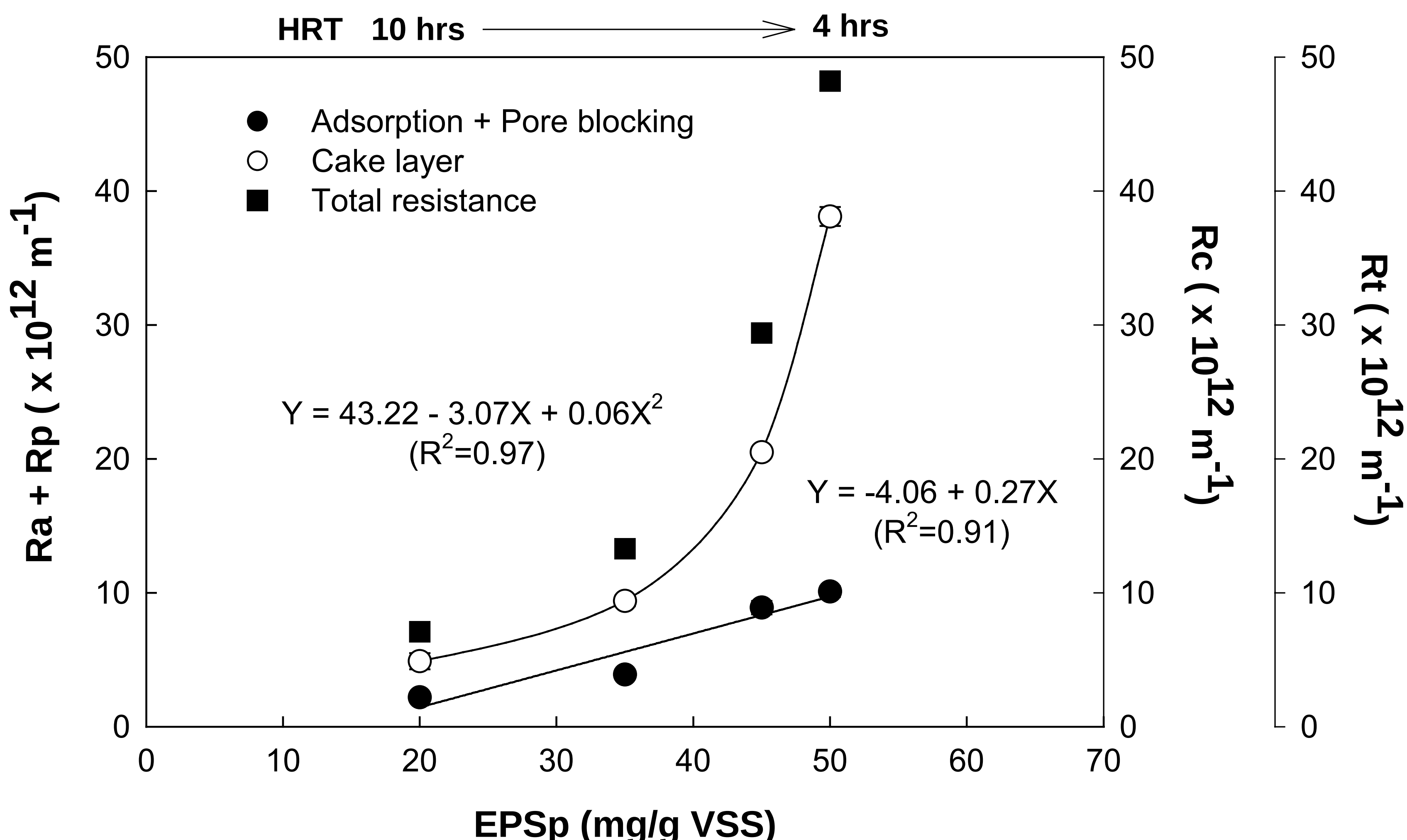
Inner side
(Black)

Outer side
(Brown)

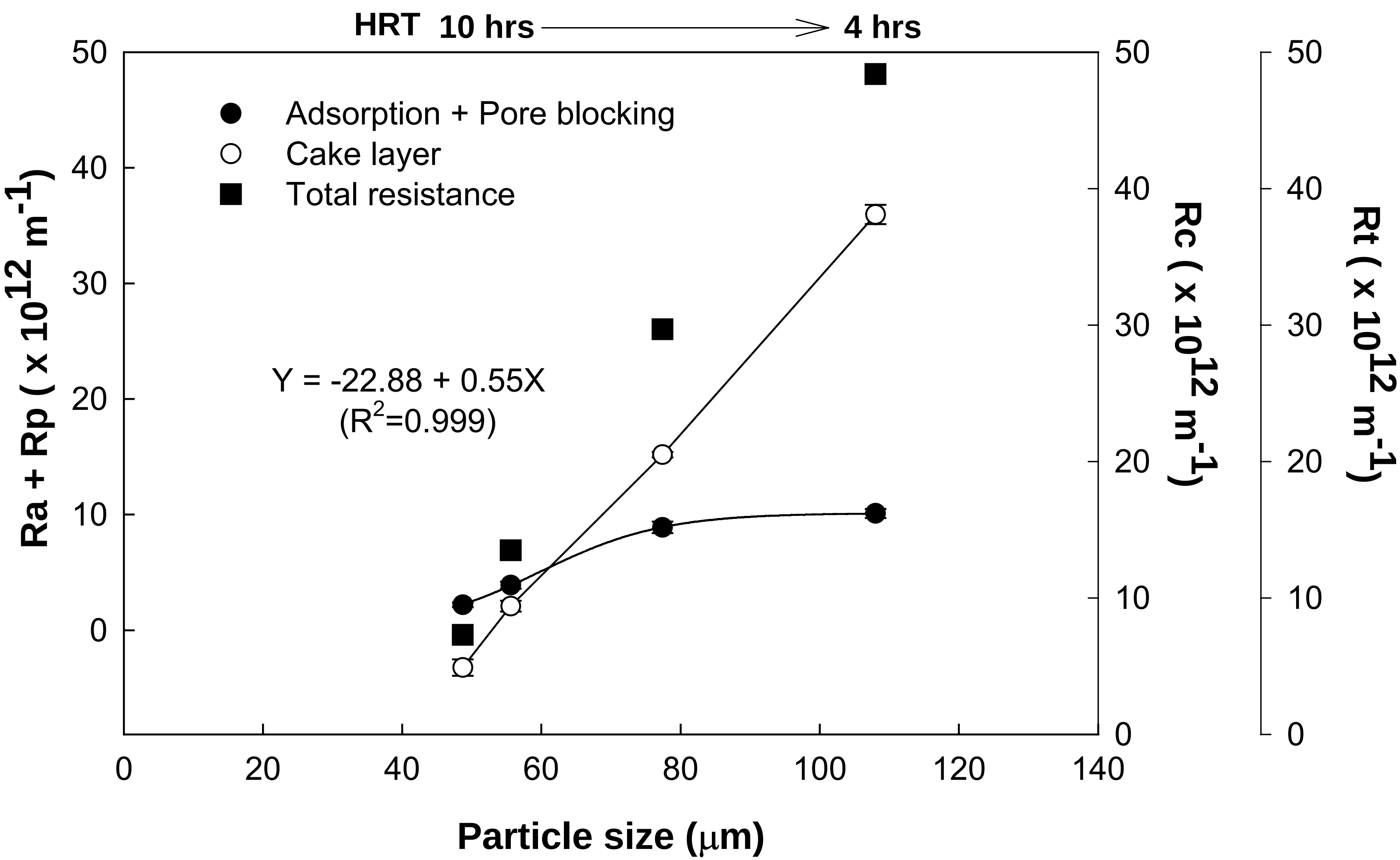
Effect of EPSc on membrane fouling



Effect of EPSp on membrane fouling



Effect of particle size on membrane fouling



Part 2: conclusions

1. Vertical-type vs. series-type MBR

▷ Vertical-type MBR; relatively low EPS and viscosity
→ reduce membrane fouling → long-term operation !

2. Lab vs. pilot-scale vertical-type MBR

▷ Pilot-scale; relatively higher values of EPS and viscosity, smaller particle size → severe fouling !

▷ Pilot-scale MBR (HRT=10 → 8 → 6 → 4 hrs)

- EPS content and particle size increased
- Cake layer resistance (Rc) was an important factor affecting total membrane resistance
- To reduce membrane fouling (Ra + Rp, Rc)
→ Back washing and turbulent flow

References

Chiemchaisri, C., Wong, Y. K., Urase, T. Yamamoto, K. (1992). Organic stabilization and nitrogen removal in membrane separation bioreactor for domestic wastewater treatment. *Wat. Sci. Technol*., **25**(10), 231-240.

Churchouse, S. and Wildgoose, D. (1999). Membrane bioreactors progress from the laboratory to full-scale use. *Membrane Technology*, 4-14.

Cote, P., Buisson, H., Pound, C., Arakaki, G. (1997). Immersed membrane activated sludge for the reuse of municipal wastewater. *Desalination*, **113**, 219-228.

Defrance, L., Jaffrin, M. Y. (1999). Comparison between filtrations at fixed TMP and fixed permeate flux. *J. Mem. Sci.,* 152, 203-210.

Futamura, O., Katoh, M., Takeuchi, K. (1994). Organic wastewater treatment by activated sludge Process using integrated type membrane separation. *Desalination*, **98**, 17-25.

Gander, M. A., Jefferson, B. and Judd, S. J. (2000). Aerobic MBRs for domestic wastewater treatment: a review with cost considerations. *Separation & Purification Technology*. **18**, 119-130.

Gunder, B. (2001). *The Membrane-Coupled Activated Sludge Process in Municipal Wastewater treatment*. Technomic Publishing Company, Inc., U.S.A.

Hong, S. P., Bae, T. H., Tak, T. M., Hong, S., Randall, A. (2002). Fouling control in activated sludge submerged hollow fiber membrane bioreactors. *Desalination*, **143**, 219-228.

Mayhew, M. and Stephenson, T. (1997). Low biomass yield activated sludge; A review. *Environ. Technol*., **18**(9), 883-892.

Mulder, M. (1996). *Basic Principal of Membrane Technology*. Kluwer Academic Publishers.

Stowa (2002). Membrane bioreactors for municipal wastewater treatment. STOWA publication number 2002-11A. IWA publishing, UK.