Let's open the biological black-box in Membrane BioReactor :

MBR for the next generation

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MBR : Worldwide Buisiness

~ thousands of installations of MBRs in the World

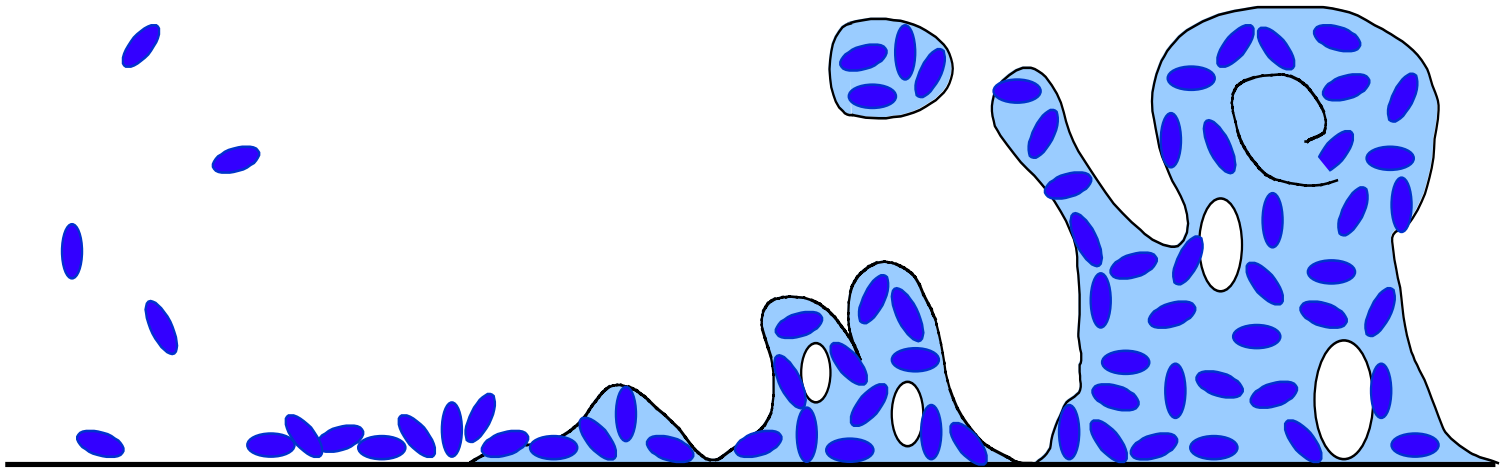
Vivendi (France), Memcore (USA)
Zenon (Canada),
Mitsubishi, Kuboda (Japan), etc..

~ 750 MBRs in Korea since last 6 years

Commercial MBR plants in Korea *2003(2002)

Membrane Manufacturer	Module type	Company	Trade mark	Membrane Material (PORE SIZE, ㎛)	Starting Year	Number of Installation	Highest capacity (M^3/d)	Fitration Mode
MRC (JAPAN)	HOLLOW FIBER MEMBRANE	KEC & HEC	SMAS & HANT	PE (0.4)	1997	403(300)	4,000(1,400)	DEAD-END FILTRATION
ZENON (CANADA)		SAE-HAN	ZENOGEM	PVDF (0.035)	2000	10(7)	1,000(300)	
KMS (KOREA)		KMS	-	PE (0.4)	2002	150(100)	600(225)	
SKC, E.N.E. (KOREA)		KOLON	KIMAS Ⅰ,Ⅱ	PSF (0.1)	1998	10(10)	-	
天津膜天社 (CHINA)		RAPAH TECH	-	PVDF (0.1-0.4)	2002	10	-	
YUASA (JAPAN)	PLATE MEMBRANE	ZENIX ENG & JIN WOO ENV.	NIX-MBR	Polyolefin (0.4)	1999	68(67)	4,000(900)	
PURE ENVI-TECH (KOREA)		PURE ENVI-TECH	-	CPVC (0.25)	2002	20(2)	350(250)	
MEMBRATEK (SOUTH AFRICA)	TUBULAR MEMBRANE	AQUATECH	BIOSUF	PES (40,000Da)	1995	50(50)	2,000(2,000)	CROSSFLOW FILTRATION
RUSSIA		ZENIX ENG.	-	PSF (30,000Da)	1996	13(13)	200(-)	
TOTAL						734(559)		

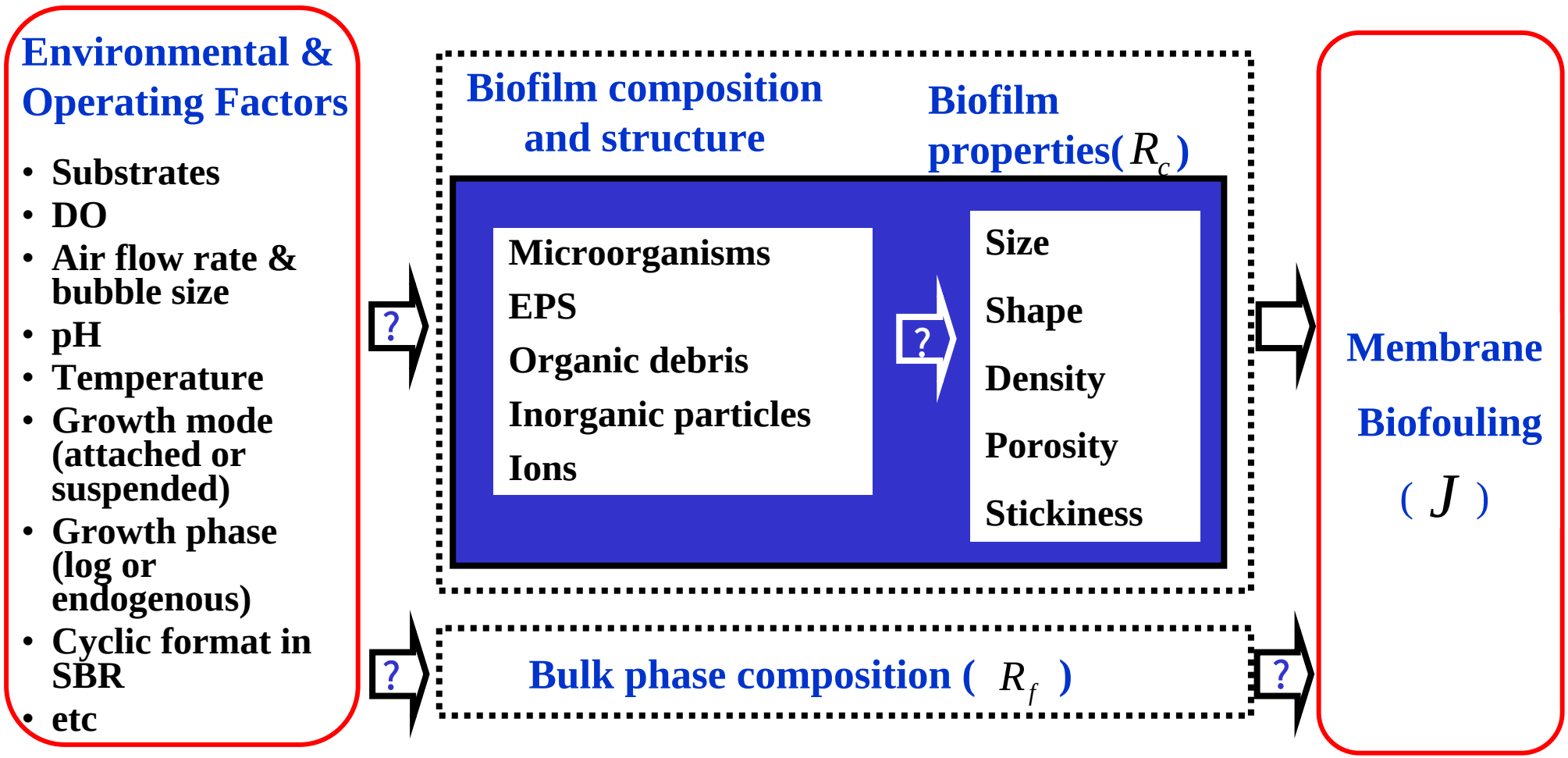
Biofouling



: Membranes in contact with the broth of activated sludge reactor will be colonized within short time by microorganisms, leading to the formation of a composite layer known as biofilm.

: Biofouling has restricted the widespread application of MBR,
because i) it limits the maximum flux obtainable,
ii) it leads to substantial cleaning requirements,
iii) it shortens membrane life time

Overview of factors leading to membrane biofouling



Biofilm in resistance in series model

$$J = \frac{\Delta P}{(R_m + R_f + R_c) \cdot \eta}$$

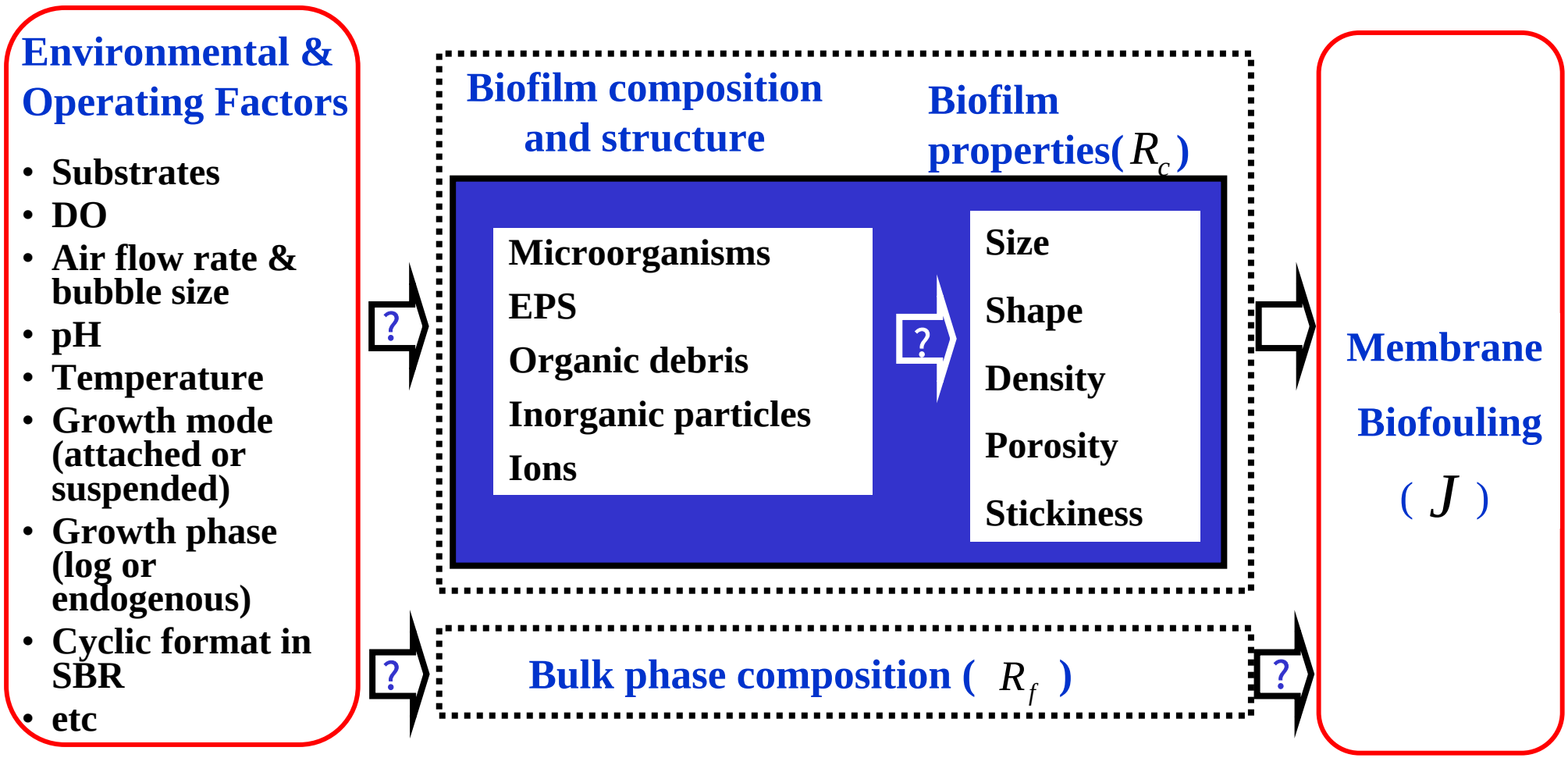
Rm : Intrinsic Membrane Resistance

R_f : Fouling layer resistance (specific membrane-solute interactions, either by surface deposition or pore fouling) ← Bulk phase Compositions

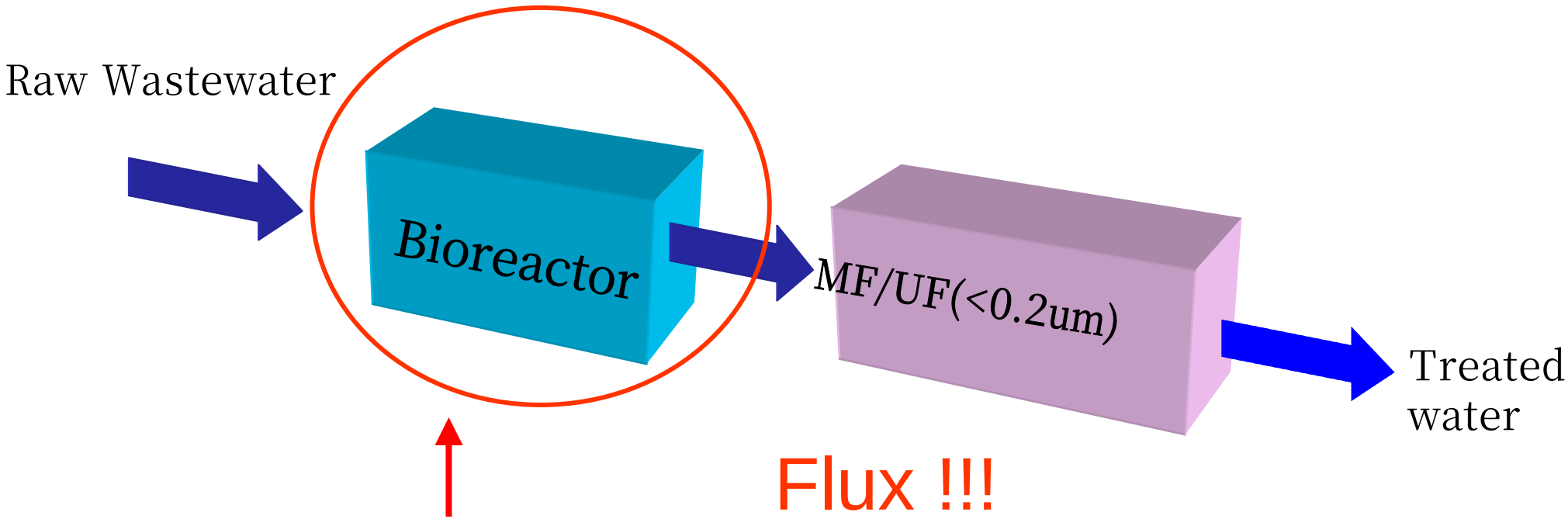
Rc : Cake layer resistance ← Biofilm (e.g., floc properties)

.

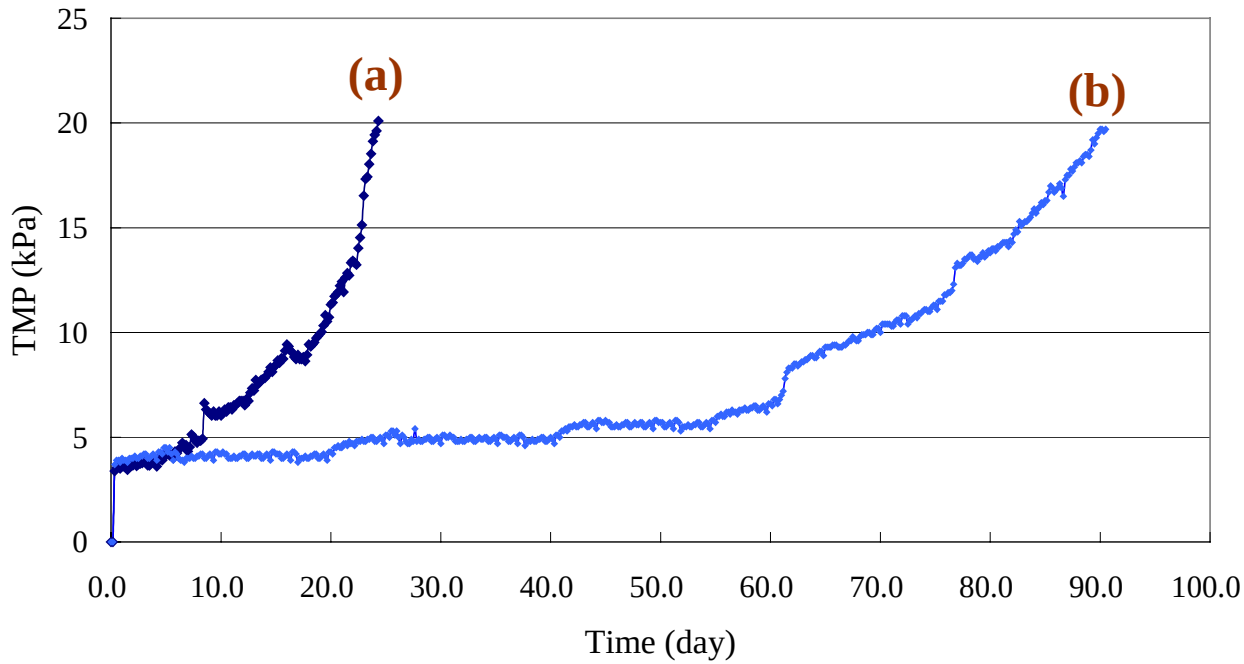
Overview of factors leading to membrane biofouling



Highlights of the past on MBR

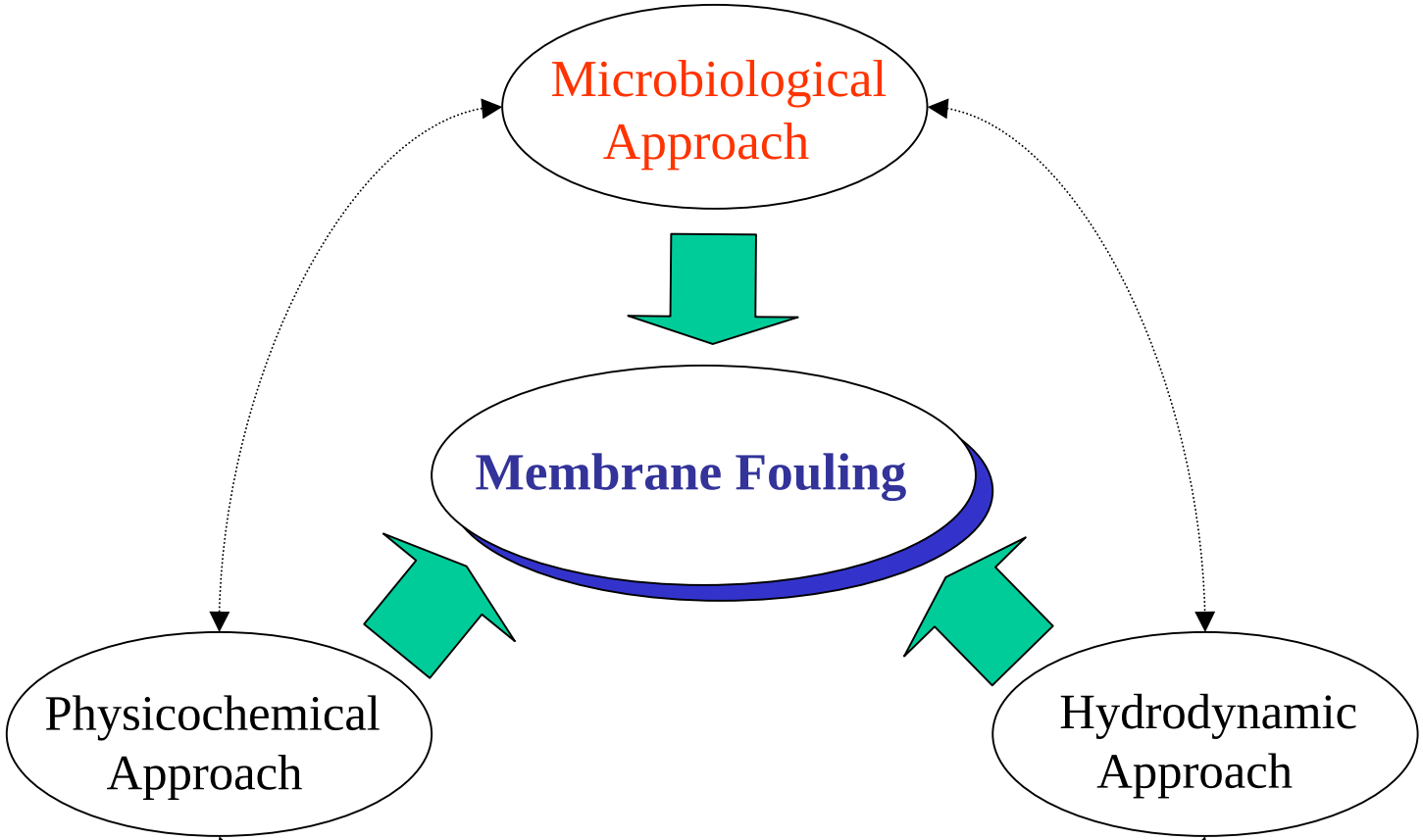


TMP profile of (a) MSBR with anoxic phase of 10 min. and (b) MSBR without anoxic phase.



	Cycle format			
	anoxic	fill	aerobic	filtration
(a)	0	10min	3hrs	50min
(b)	10min	10min	2hrs 50min	50min

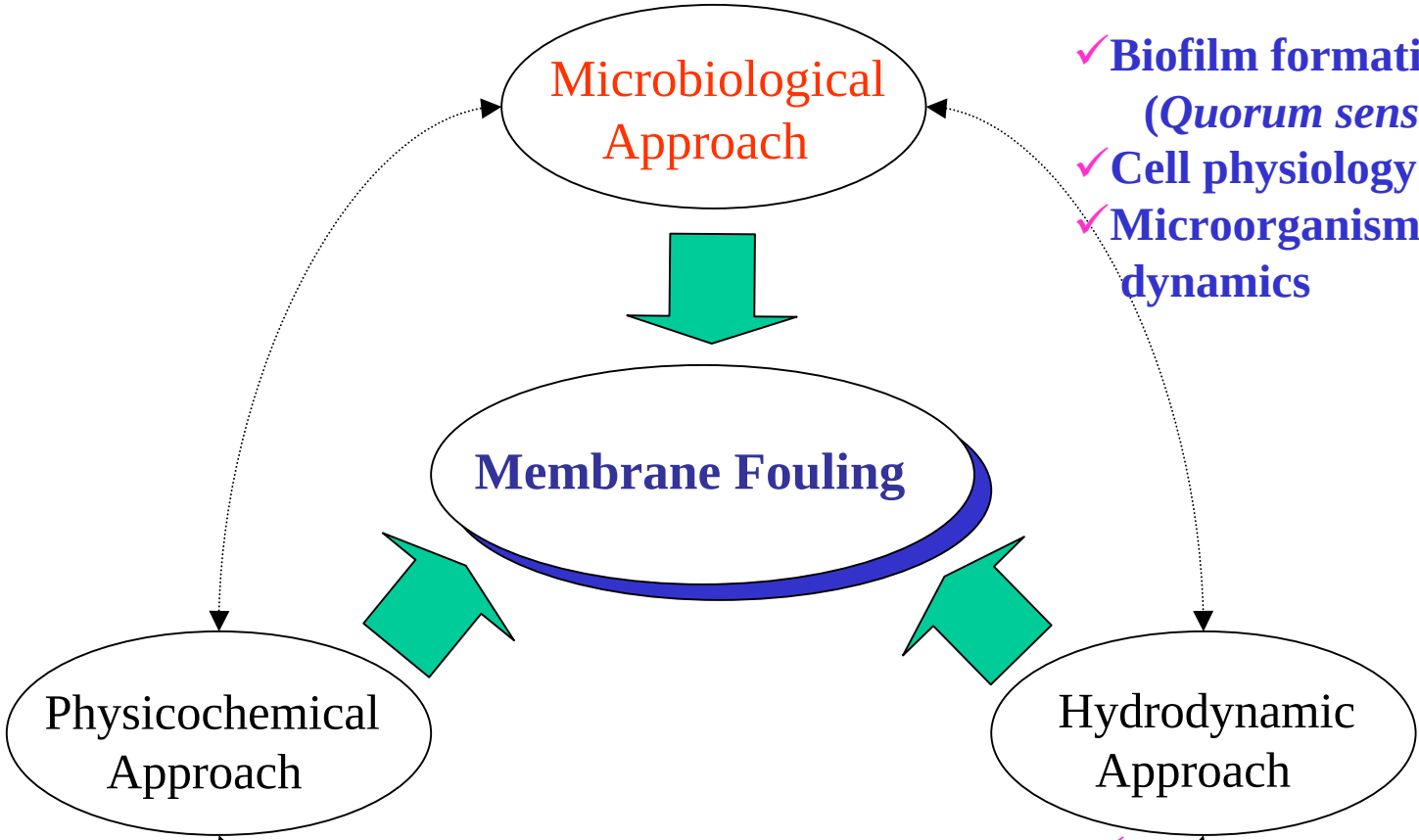
Membrane Fouling



- ✓**Membrane materials**
- ✓**Membrane surface modification**
- ✓**Hybrid system**
- ✓**Chemical additives**
- ✓**Surface chemistry**

- ✓**Flow regime:**
  (*side stream vs. submerged*)
- ✓**Module type:**
  (*tubular, plate,hollow fiber*)
- ✓**Critical flux**

Membrane Fouling



- ✓Biofilm formation mechanism (*Quorum sensing, etc.)*
- ✓Cell physiology& morphology
- ✓Microorganism population dynamics

- ✓Membrane materials
- ✓Membrane surface modification
- ✓Hybrid system
- ✓Chemical additives
- ✓Surface chemistry

- ✓Flow regime: (*side stream vs. submerged*)
- ✓Module type: (*tubular, plate,holow fiber*)
- ✓Critical flux

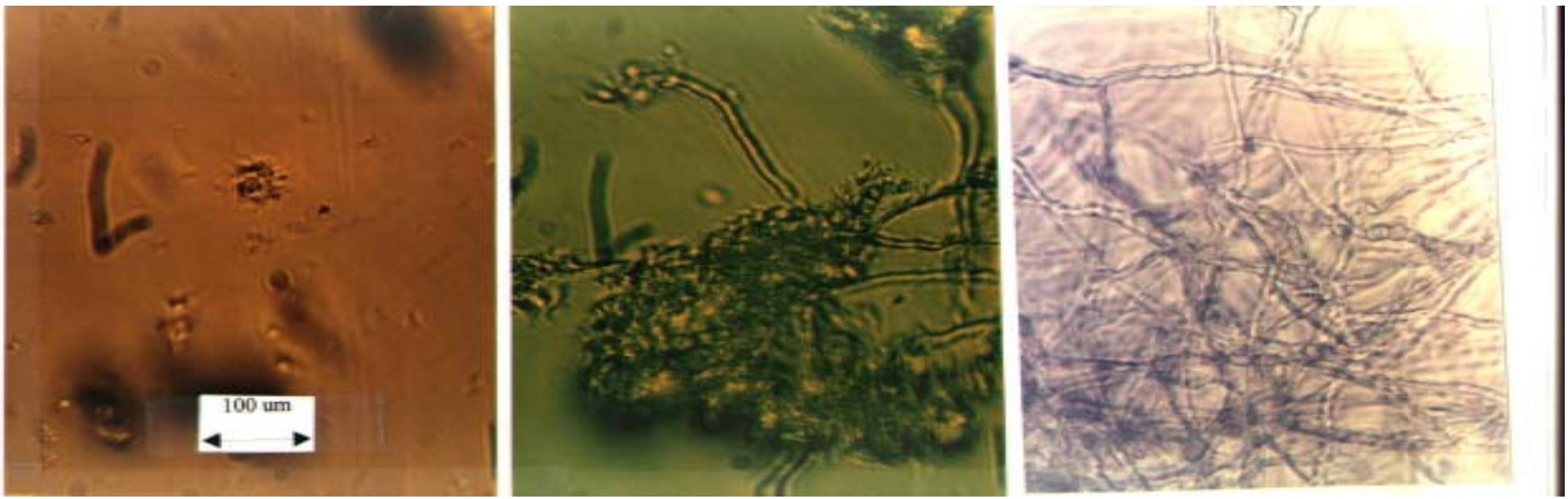
Let`s Open the Black box in MBR

✓*Morphology of activated sludge*

Hybrid system (Biological activated carbon)
Cell physiology (Growth phase)
Cell physiology (DO concentration)
Cell physiology (Cycle Format in SBR)
Cell physiology (Pump Shear)
Growth mode (Suspended vs. Attached)
Conclusion and Research on MBR in 21C

Effect of Floc Morphology on Membrane Fouling

- Pin point floc (left)
- Bulking sludge (right)
- Normal activated sludge (center)



Effect of Floc Morphology on Membrane Fouling

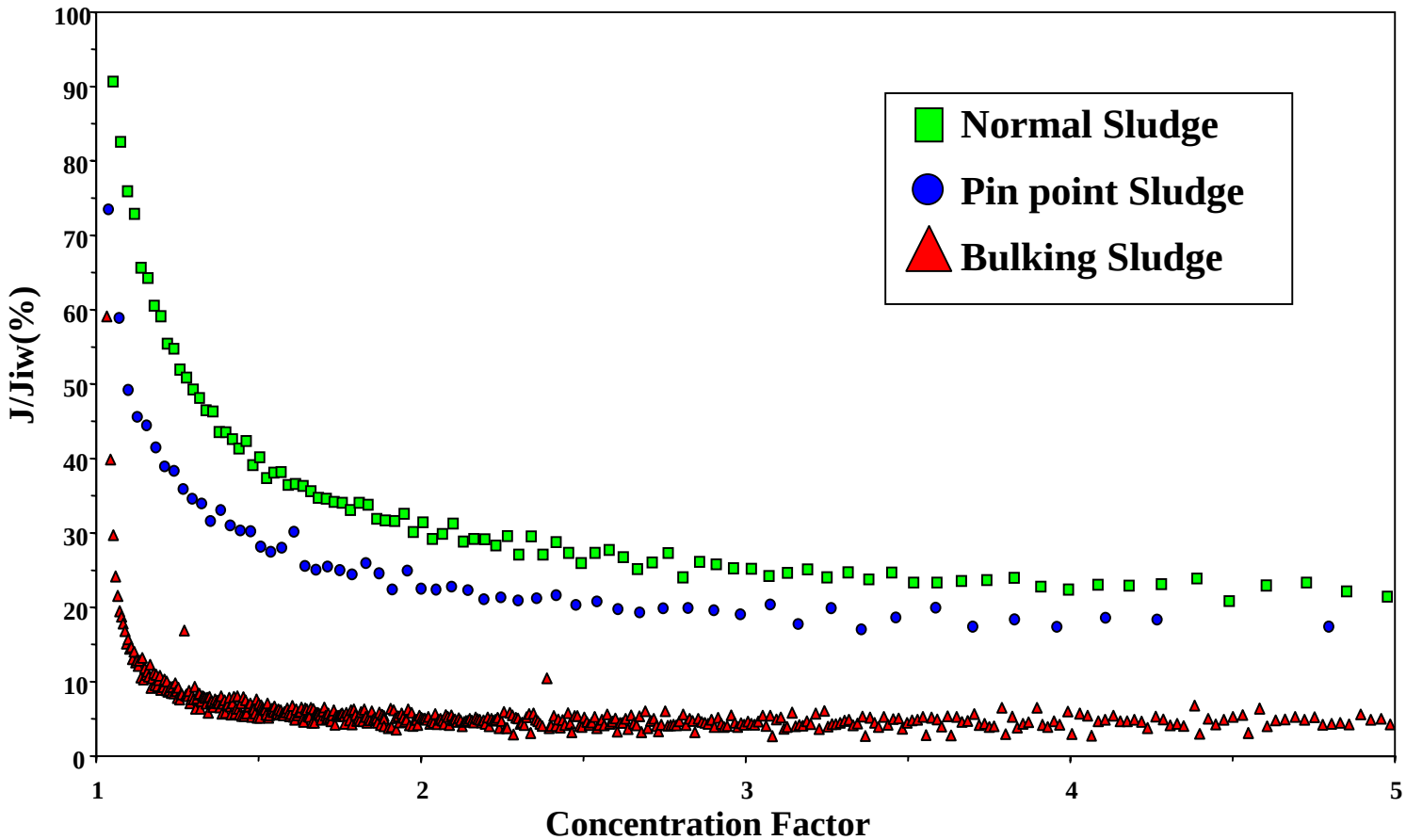
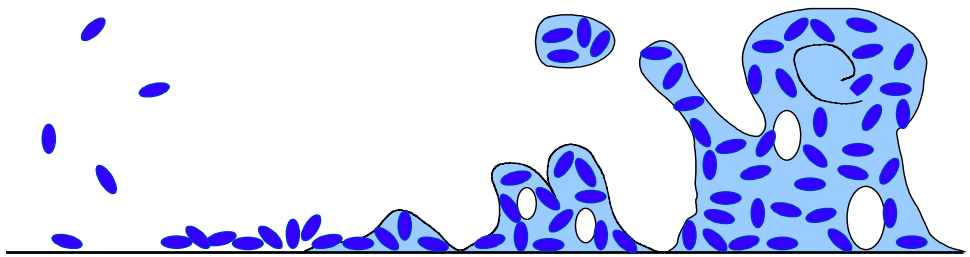


Fig. 3b Flux declines according to floc structures during ultrafiltration of activated sludge with PM30 membrane

Analysis of resistances in MBR



ΔP_t; Pressure drop
μ ; Fluid viscosity
ε ; Porosity
L ; Cake layer thickness
ψ ; sphericity
k ; Kozeny constant
d_p ; Particle diameter

$$J = \frac{\Delta P_t}{\mu(R_m + R_c + R_f)}$$

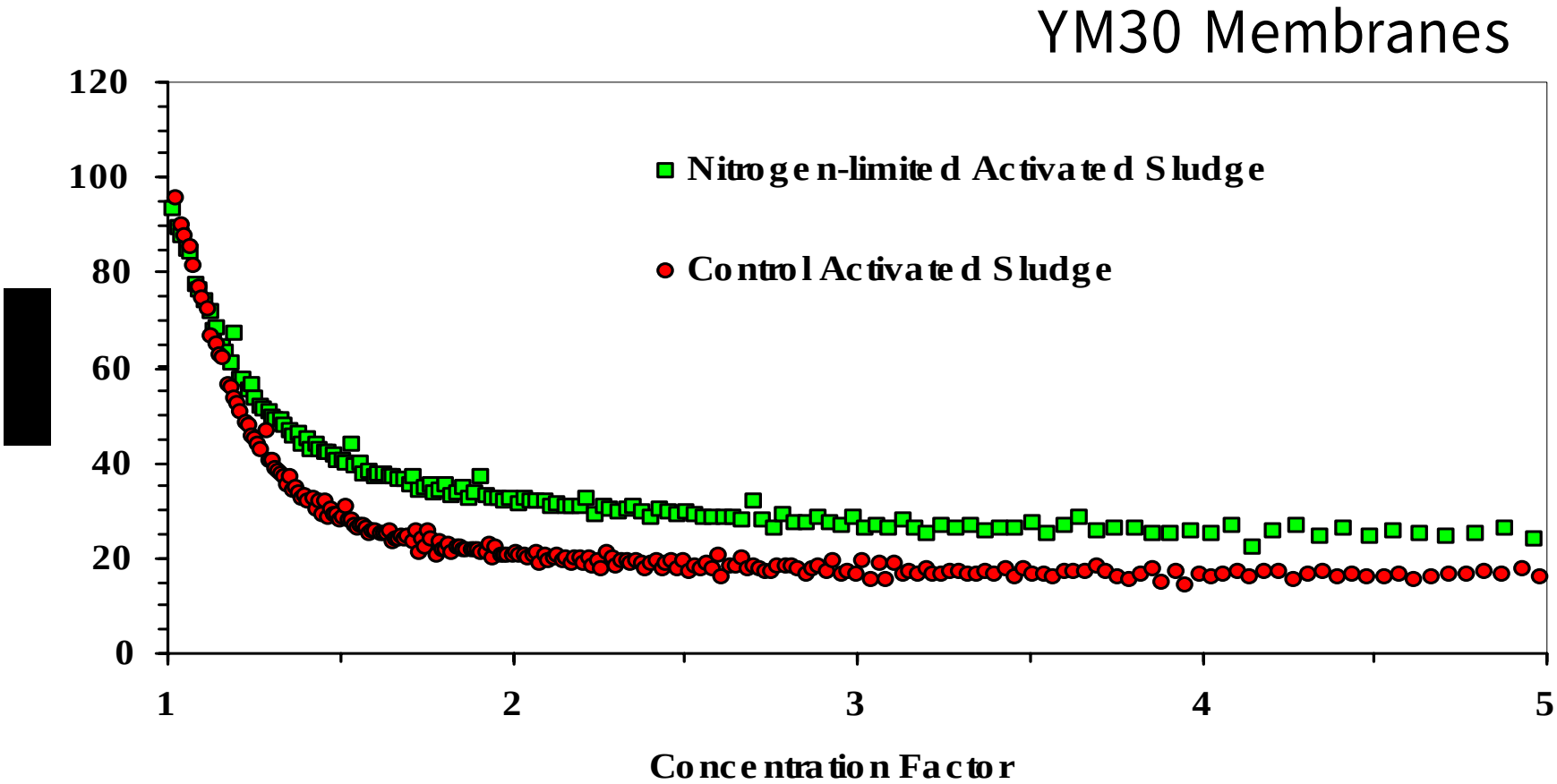
$$R_m = f(\text{Membrane Material, Pore size, etc.})$$

$$R_c = f(\text{Deposited microbial flocs, biofilm})$$

$$= Lk\left(\frac{6}{\psi d_p}\right)^2 \cdot \frac{(1-\varepsilon)^2}{\varepsilon^3}$$

$$R_f = f(\text{Membrane Meterial, EPS, SMP, etc.})$$

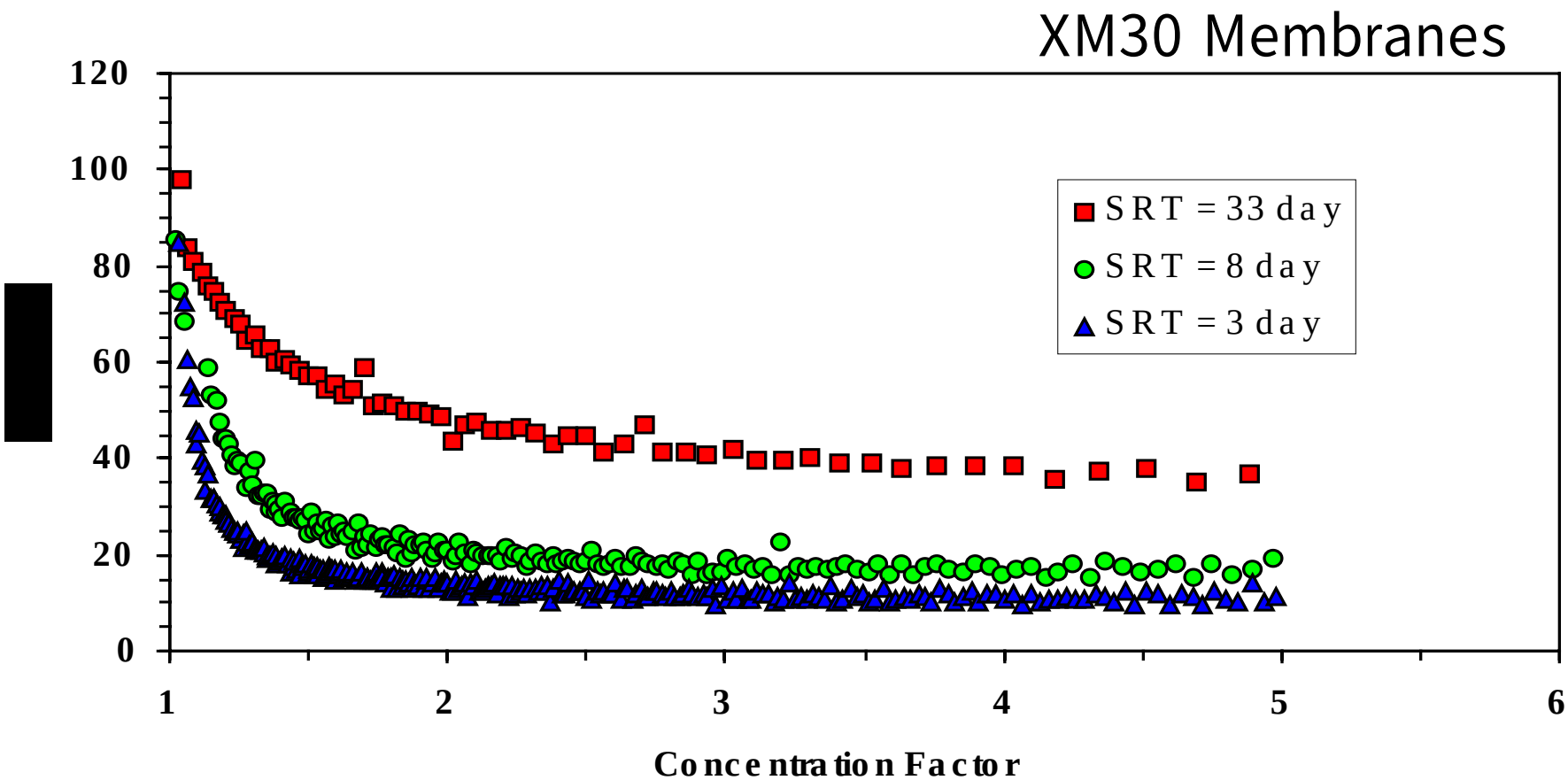
N- limited Activated sludge



EPS contents under different nutrient condition

Sludge Type	R_m ($10^{11} \times m^{-1}$)	R_c ($10^{11} \times m^{-1}$)	R_f ($10^{11} \times m^{-1}$)	R_t ($10^{11} \times m^{-1}$)	R_c/R_t (%)	EPS (VS mg/g MLSS)
Control	19	97	1	117	83	245
N-limitation	18	57	2	77	74	151

Effect of SRT on Membrane Flux



EPS content of activated sludge flocs at different SRT

SRT	EPS content	
	Range (VS mg/g MLSS)	Average (VS mg/g MLSS)
3 days	234 276	268
8 days	228 273	244
33 days	187 242	213

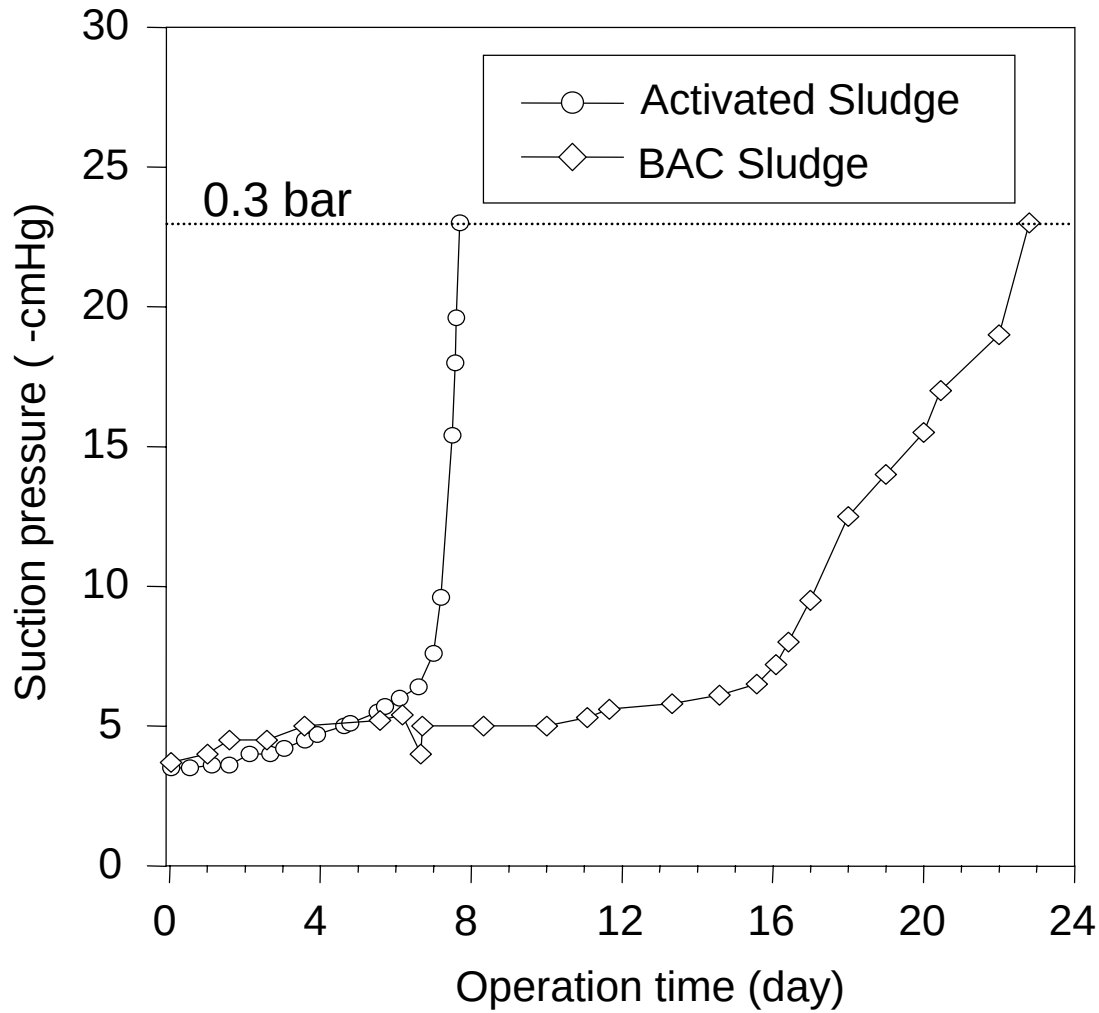
Let`s Open the Black box in MBR

Morphology of activated sludge

✓***Hybrid system (Biological activated carbon)***

Cell physiology (Growth phase)
Cell physiology (DO concentration)
Cell physiology (Cycle Format in SBR)
Cell physiology (Pump Shear)
Growth mode (Suspended vs. Attached)
Conclusion and Research on MBR in 21C

Addition of PAC in MBR



- Filtration
  PE 0.1 μm, 0.056 m^2
  Flux 15 $L/m^2/hr$
  air flow : 2.0 L/min

- Bioreactor
  MLSS: 6,000~10,000
  HRT 4~6 hour
  SRT 25~40 day
  Loading
  2.2~2.4
  ($kgCOD/m^3/day$)

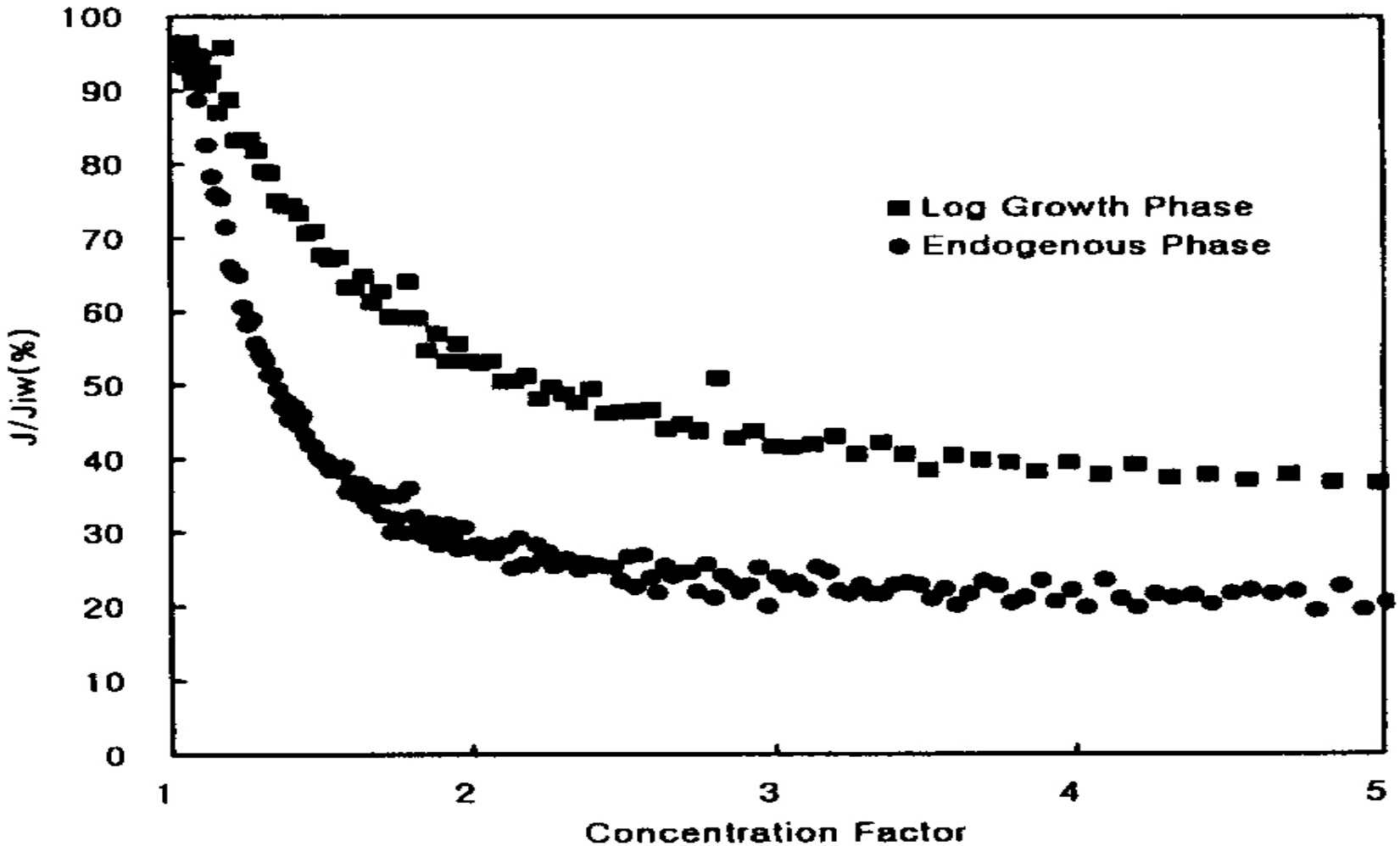
Let`s Open the Black box in MBR

Morphology of activated sludge

Hybrid system (Biological activated carbon)

✓*Cell physiology (Growth phase)*
Cell physiology (DO concentration)
Cell physiology (Cycle Format in SBR)
Cell physiology (Pump Shear)
Growth mode (Suspended vs. Attached)
Conclusion and Research on MBR in 21C

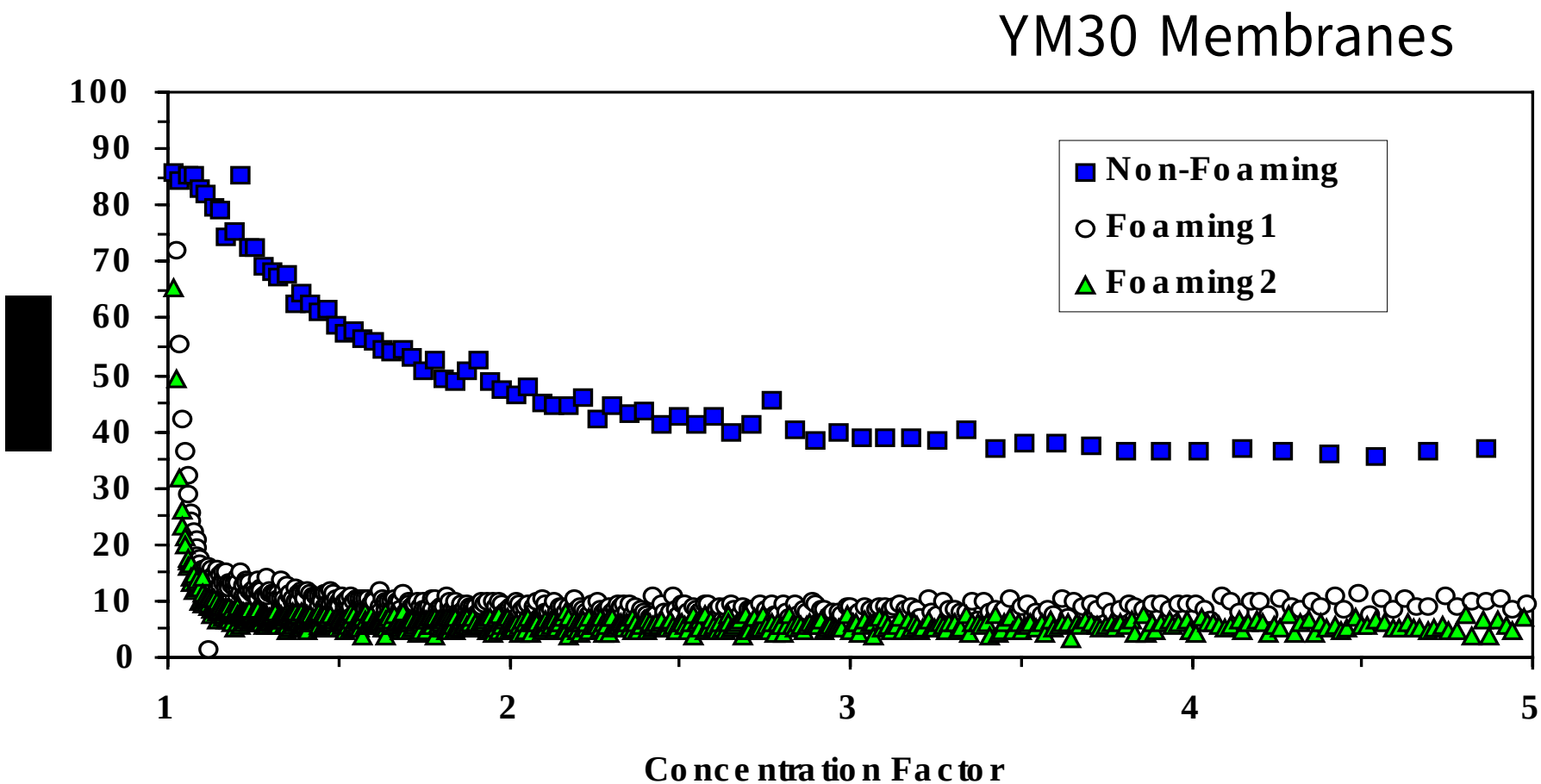
Effect of Physiological states of Activated Sludge on Membrane Biofouling



EPS contents of activated sludge flocs at different growth phase

	R_m ($10^{11} \times m^{-1}$)	R_c ($10^{11} \times m^{-1}$)	R_f ($10^{11} \times m^{-1}$)	R_t ($10^{11} \times m^{-1}$)	R_c/R_t (%)	EPS (VS mg/g MLSS)
YM30						
Log growth phase	18	33	0.1	51	65	200
Endogenous phase	20	63	0.1	83	76	270
PM30						
Log growth phase	4	42	13	59	71	200
Endogenous phase	3	82	11	96	85	270

Effect of Foaming on Membrane Biofouling



Hydrophobicity of foaming and non-foaming activated sludge

Characteristic of activated sludge	Relative Hydrophobicity(%)	
	Range	Average
non-foaming	54 60	57
foaming 1	65 93	80
foaming 2	62 91	82

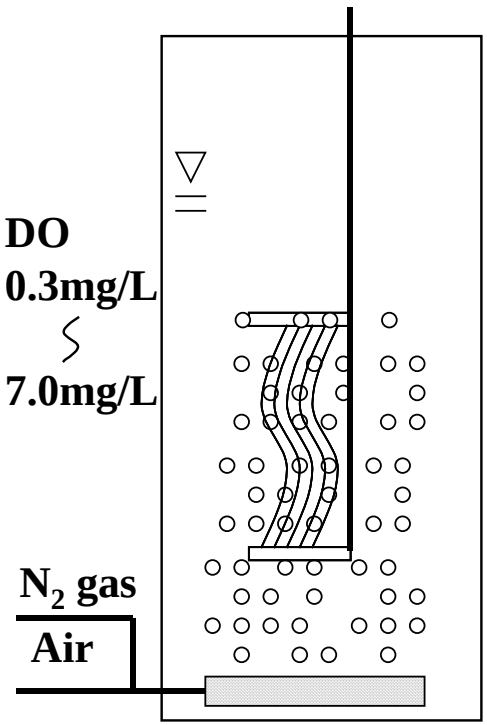
Let`s Open the Black box in MBR

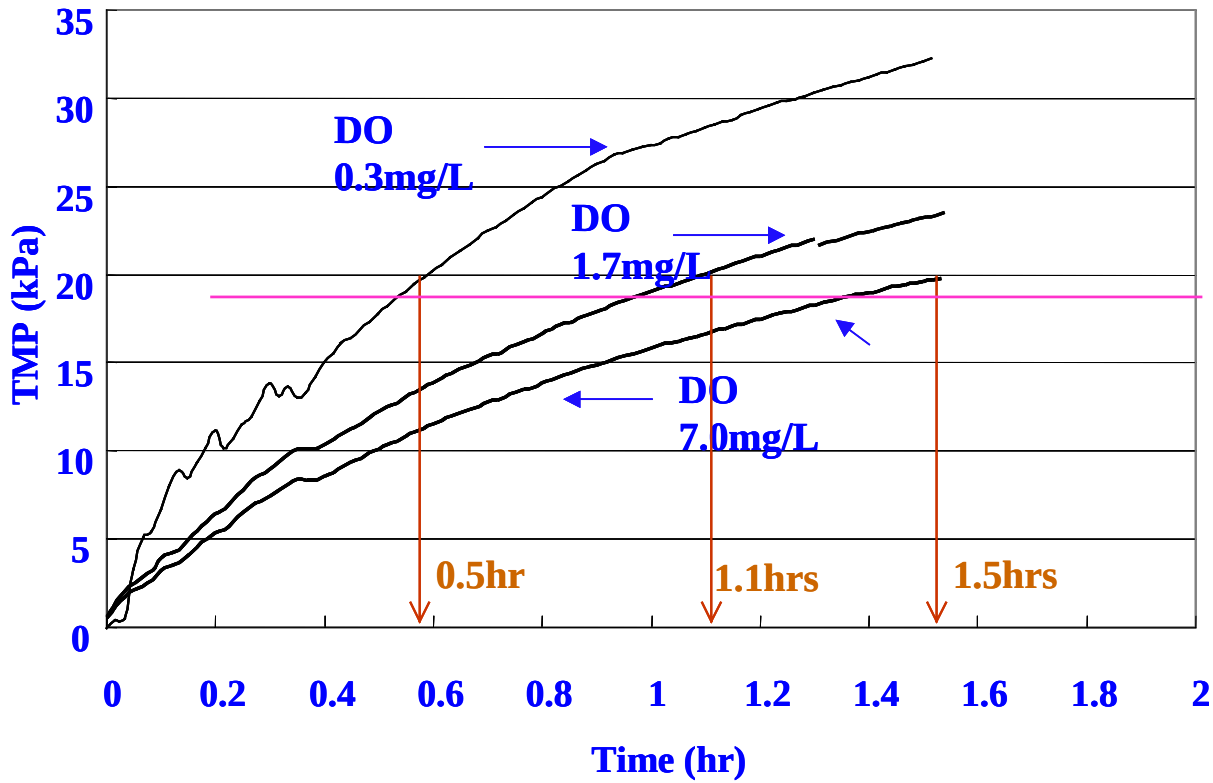
Morphology of activated sludge

Hybrid system (Biological activated carbon)
Cell physiology (Growth phase)

✓*Cell physiology (DO concentration)*
Cell physiology (Cycle Format in SBR)
Cell physiology (Pump Shear)
Growth mode (Suspended vs. Attached)
Conclusion and Research on MBR in 21C

TMP profiles at various DO concentrations under constant pneumatic mixing intensity





Let`s Open the Black box in MBR

Morphology of activated sludge

Hybrid system (Biological activated carbon)
Cell physiology (Growth phase)
Cell physiology (DO concentration)

✓*Cell physiology (Cycle Format in SBR)*
Cell physiology (Pump Shear)
Growth mode (Suspended vs. Attached)
Conclusion and Research on MBR in 21C

Effect of Cycle Format on Membrane Fouling in Membrane-coupled Sequencing Batch Reactor(SBR)

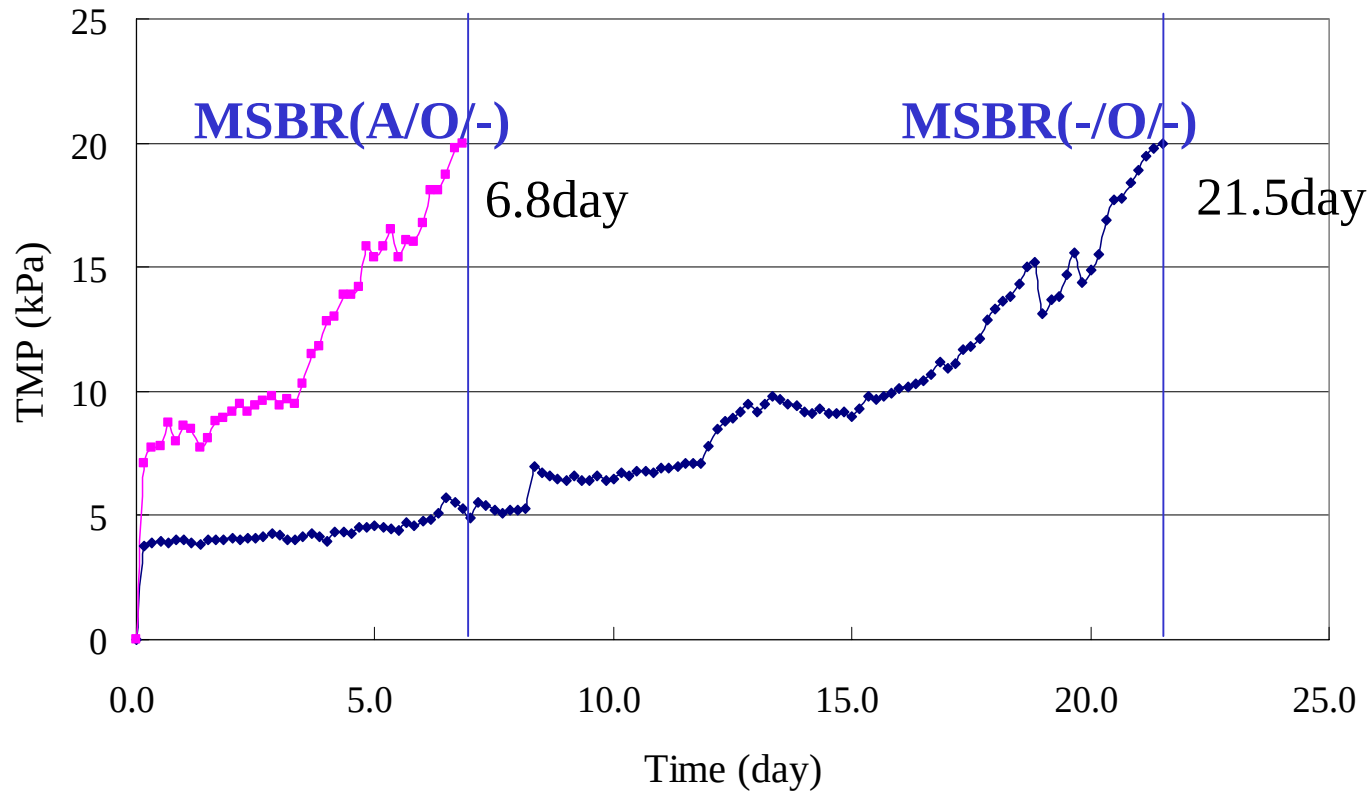
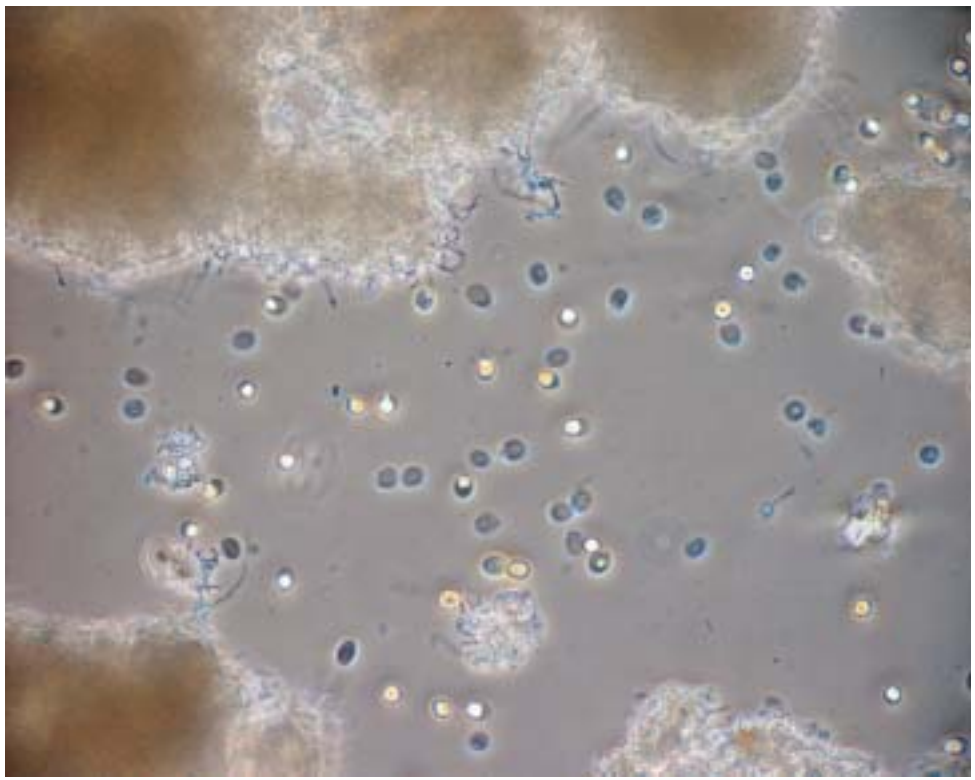


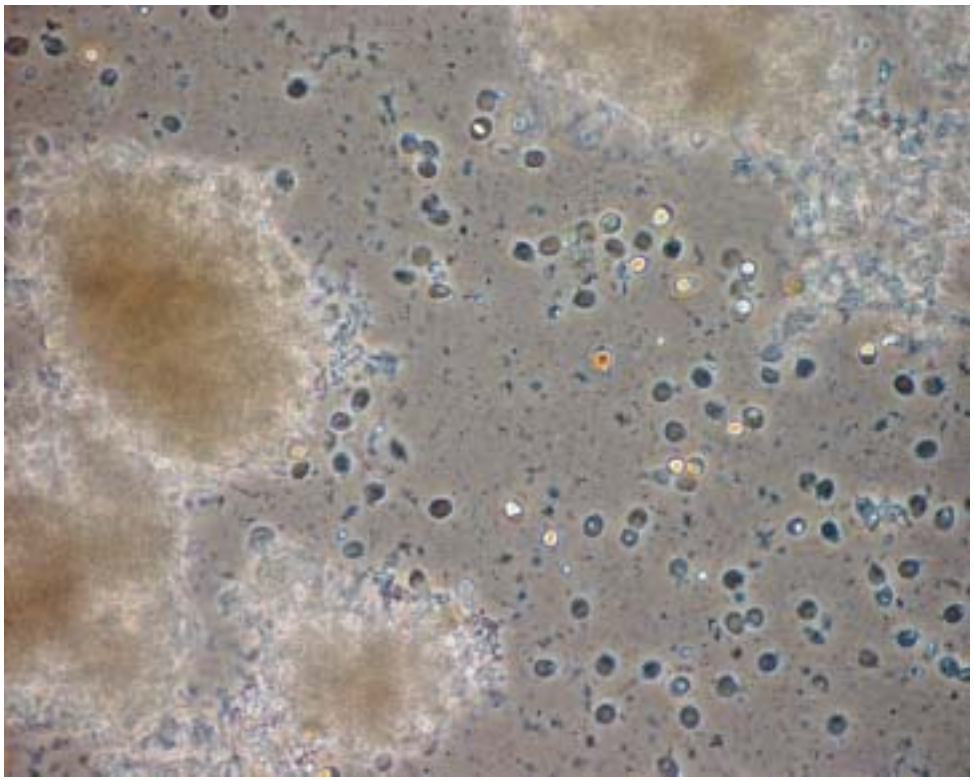
Image analysis

(-/O/-)



x200

(A/O/-)



x200

MSBR(A/O/-); MSBR with anoxic phase

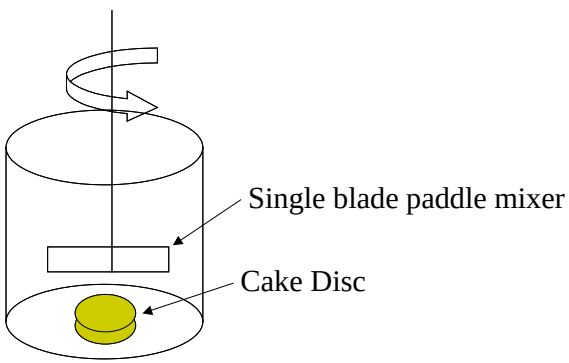
MSBR(-/O/-); MSBR without anoxic phase

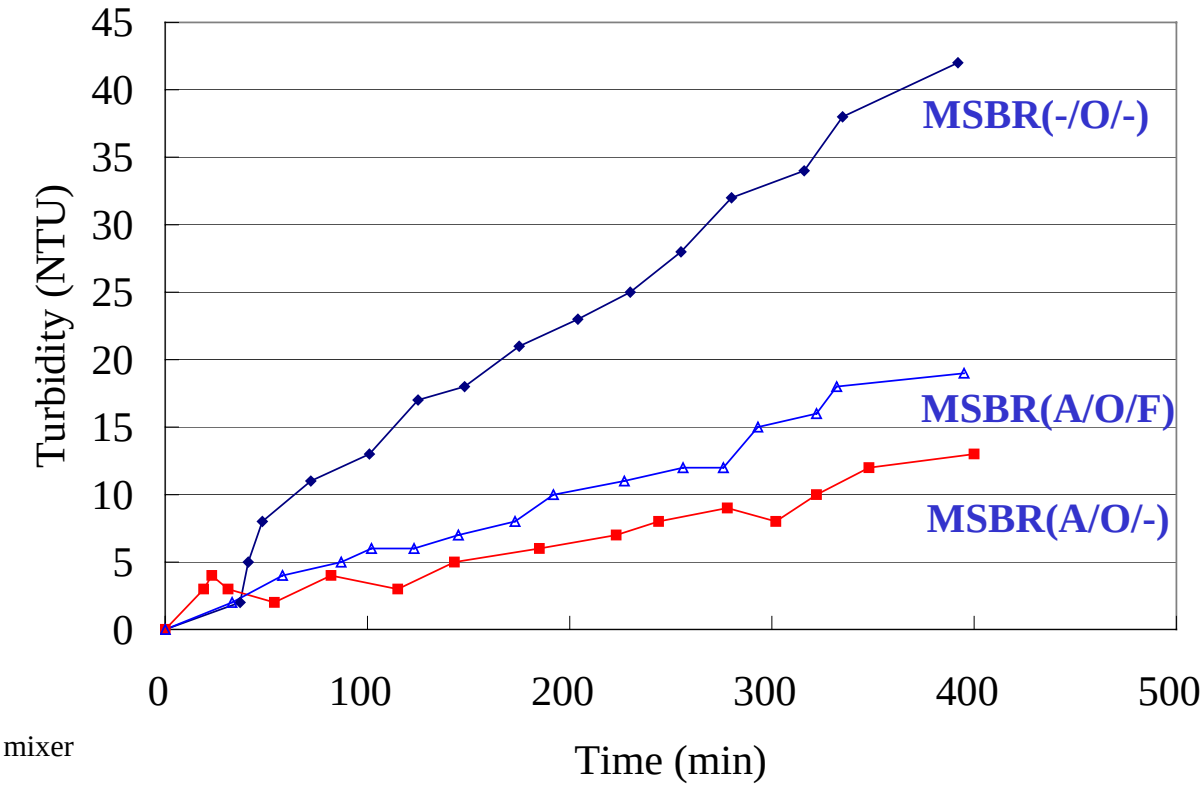
EPS analysis in Membrane –coupled SBR

	EPS (bound)		EPS (soluble)	
	Protein	Polysaccharide	Protein	Polysaccharide
MSBR(- /O/ -) (mg/L)	35.8 (±1.7)	66.5 (±1.9)	1.0 (± 0.1)	2.2 (± 0.2)
MSBR(A/O/ -) (mg/L)	24.1 (±1.4)	52.7 (±1.8)	2.4 (± 0.2)	5.0 (± 0.2)

( ) : standard deviation

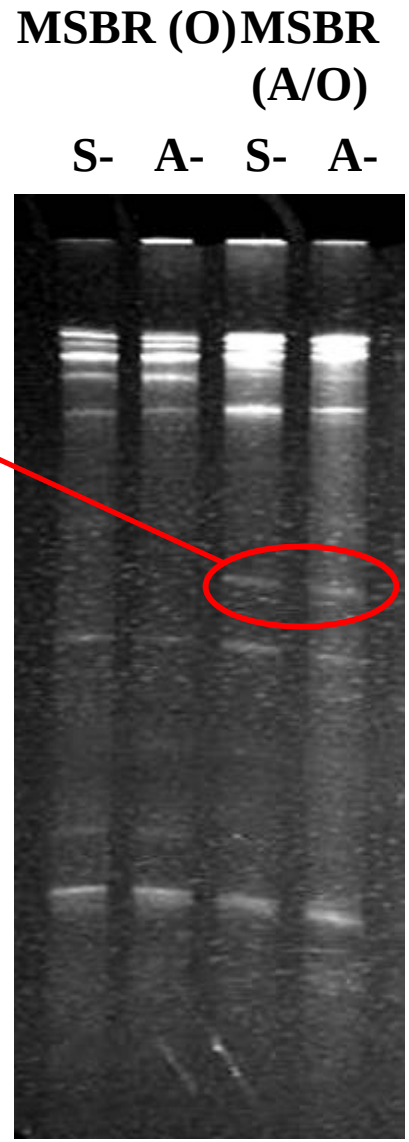
Stickiness of Biofilm vs. cycle format in SBR





MSBR(A/O/-); MSBR with anoxic phase
MSBR(-/O/-); MSBR without anoxic phase

Phylum. Proteobacteria phy.
Class. BetaProteobacteria
Order. Burkholderiales
Family. *Comamonadaceae*
Genus. *Diaphorobacter*



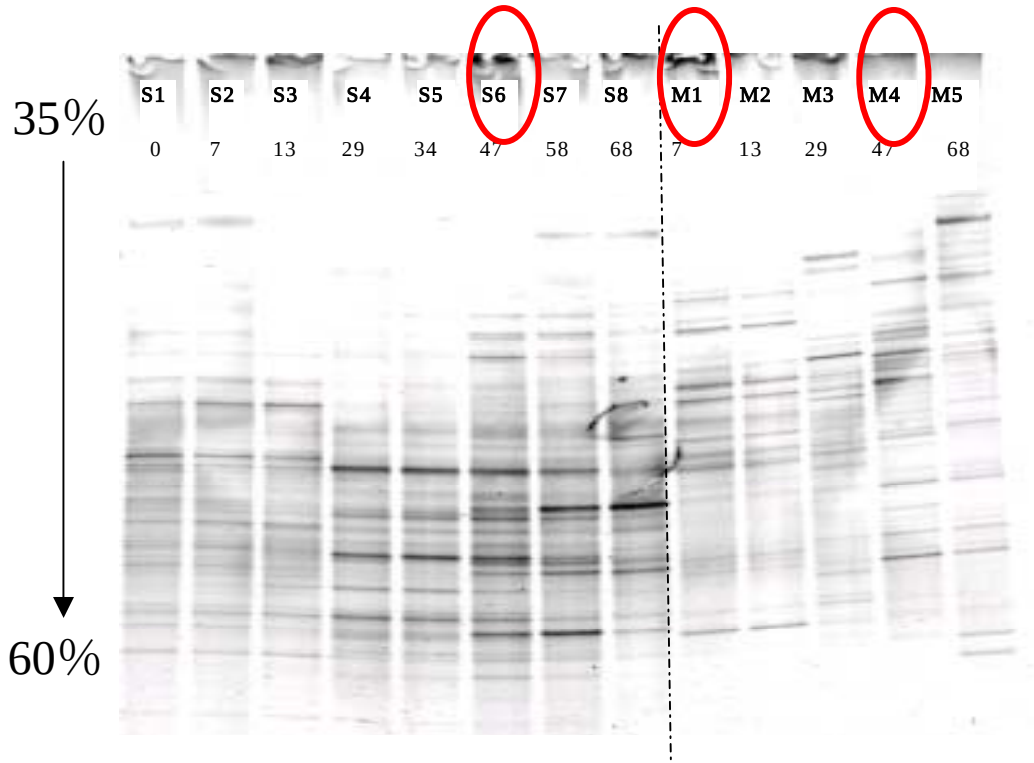
Khan,S.T.,*et al* . Appl. Environ. Microbiol. 68 (7), 3206-3214 (2002) :

Comamonadaceae, are primary PHBV-degrading denitrifiers in activated sludge.

S- : Suspended

A- : Attached

Distribution of microorganisms between bulk phage and membrane



DGGE profile (Yamamoto et al.,2004)

Lane	Operation time(day)	MLSS (mg/l)
S1	0	1720
S2,M1	7	2170
S3,M2	13	2040
S4,M3	29	2200
S5	34	2460
S6,M4	47	3400
S7	58	3860
S8,M5	68	3640

- ✓Membrane and sludge have different DGGE band patterns
- ✓Microbe on membrane surface was selectively grown

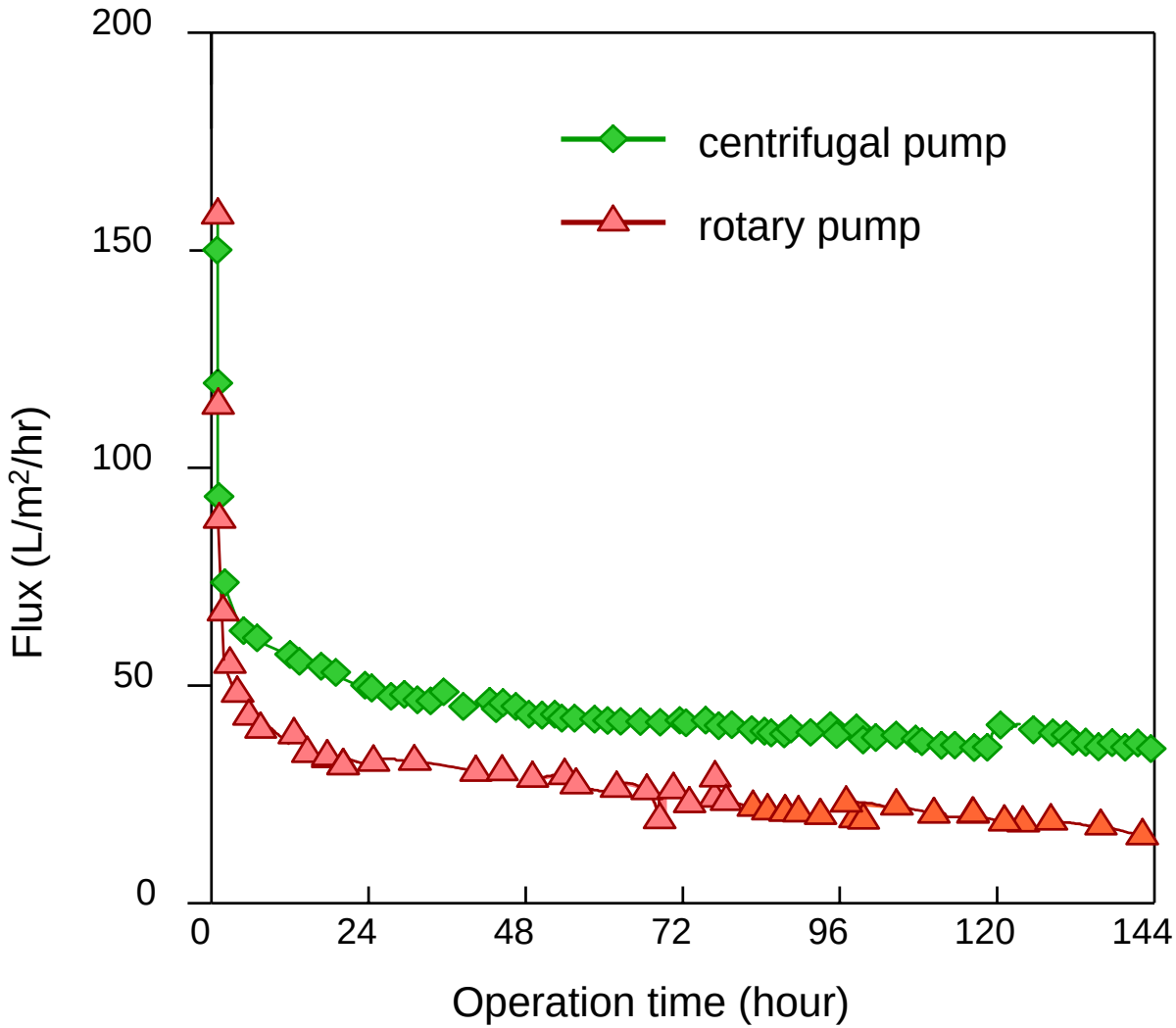
Let`s Open the Black box in MBR

Morphology of activated sludge

Hybrid system (Biological activated carbon)
Cell physiology (Growth phase)
Cell physiology (DO concentration)
Cell physiology (Cycle Format in SBR)

✓*Cell physiology (Pump Shear)*
Growth mode (Suspended vs. Attached)
Conclusion and Research on MBR in 21C

Effect of pumping device on flux in crossflow MBR



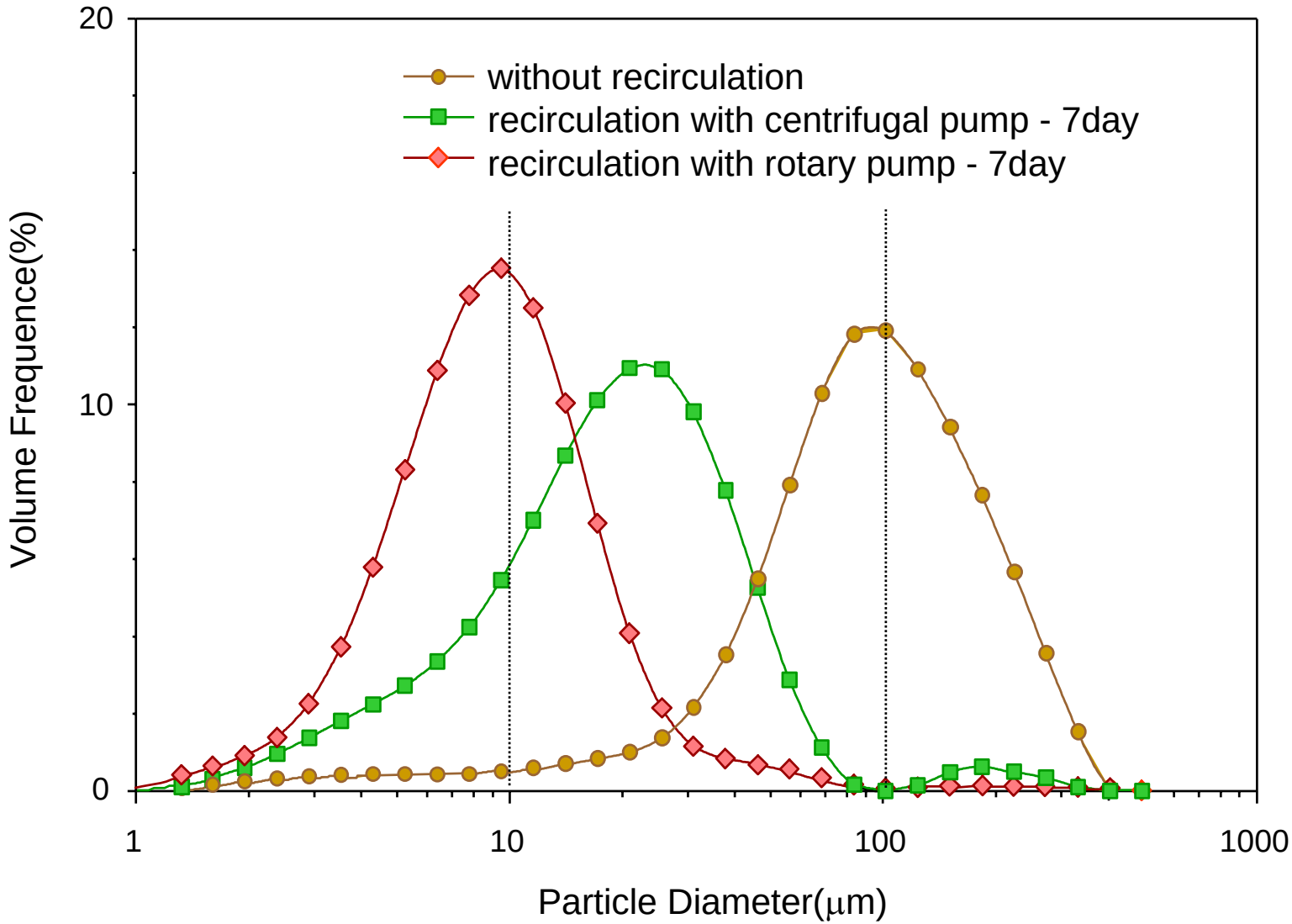
Resistance Analysis

- Resistance-in-series model

$$J = \frac{\Delta P}{\mu \cdot R_t} = \frac{\Delta P}{\mu \cdot (R_m + R_c + R_f)}$$

Resistance ($10^{12}m^{-1}$)	Pump type	
	Rotary	Centrifugal
R_m	0.63	060
R_c	17.9	10.8
R_f	0.62	0.44
R_t	19.1	11.8

* Resistance after 7 days' crossflow operation


20
10
0
Volume Frequence(%)
without recirculation
recirculation with centrifugal pump - 7day
recirculation with rotary pump - 7day
1
10
100
1000
Particle Diameter(μm)

Sludge Production in MBR system :
Observed sludge yields in conventional activated sludge and in crossflow MBR

Pump type	Conventional activated sludge	MBR with a rotary pump	MBR with a centrifugal pump
Observed sludge yield (gMLVSS/gCOD)	0.4~0.5	0.2	0.3

Let`s Open the Black box in MBR

Morphology of activated sludge

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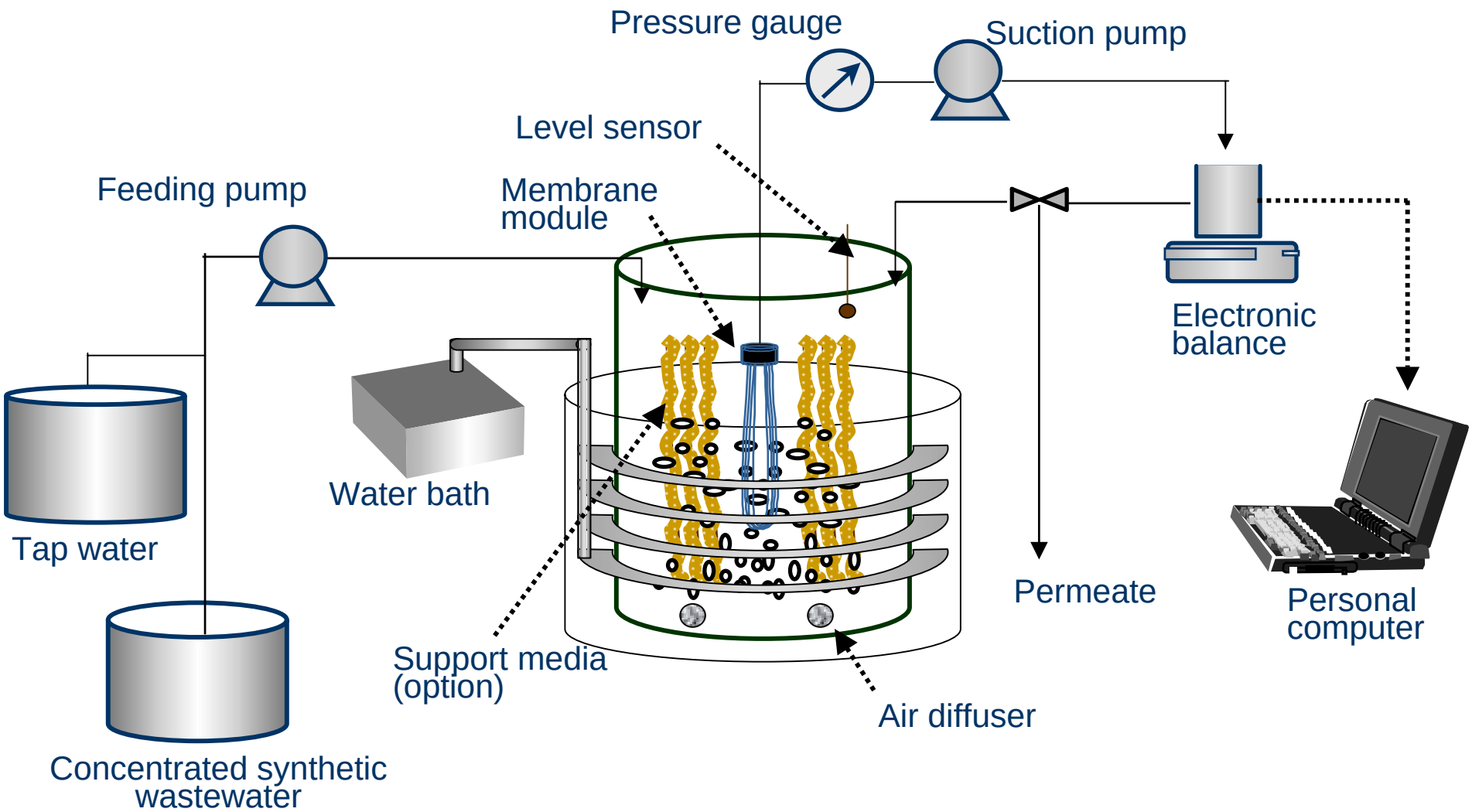
Cell physiology (Pump Shear)

✓ *Growth mode (Suspended vs. Attached)*
Conclusion and Research on MBR in 21C

Membrane- coupled Fixed bed bioreactor

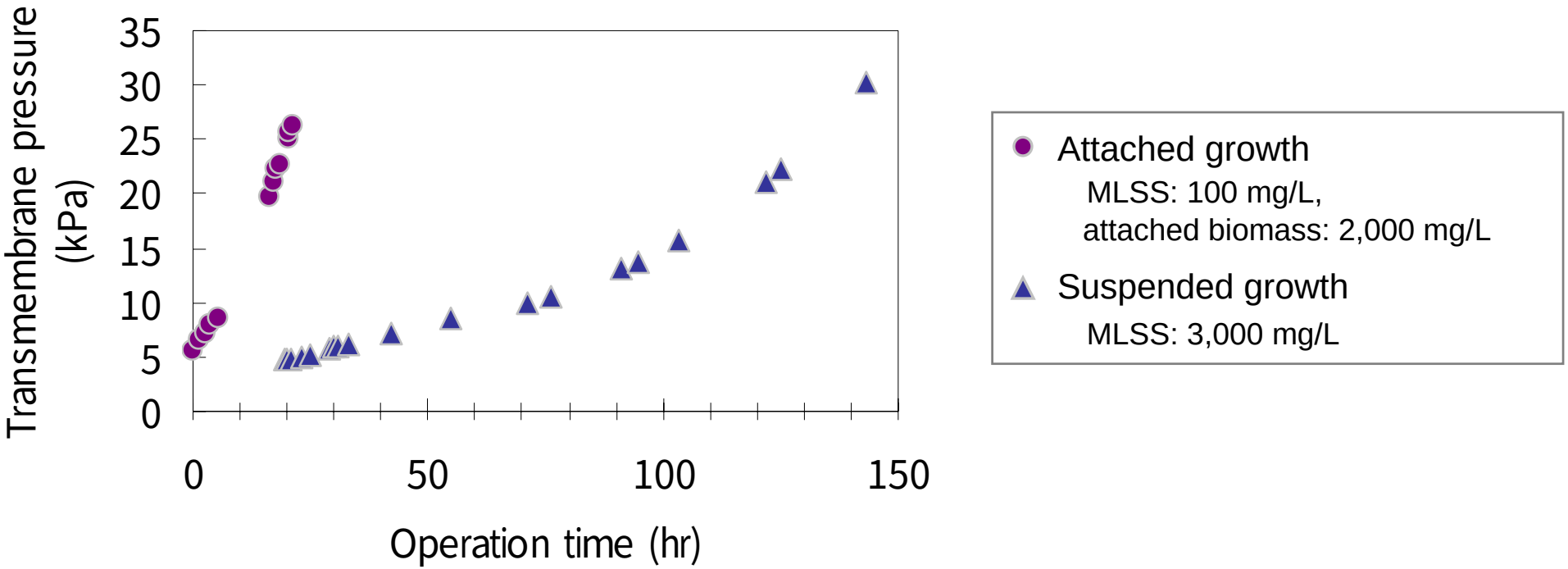


Suspended vs.Attached

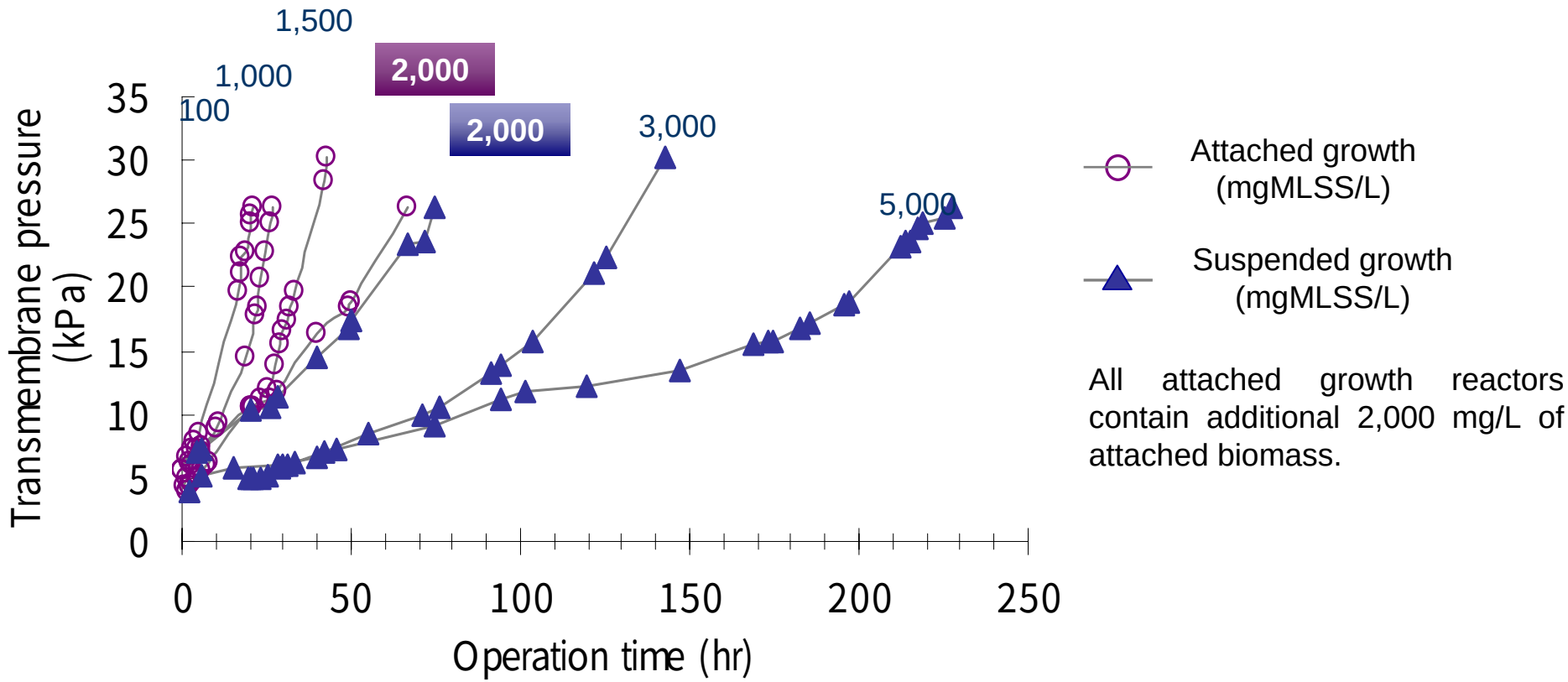
Attached Growth Reactor
(MLSS: 100~2,000 mg/L, attached biomass: 2,000 mg/L)

Suspended Growth Reactor
(MLSS: 2,000~5,000 mg/L)

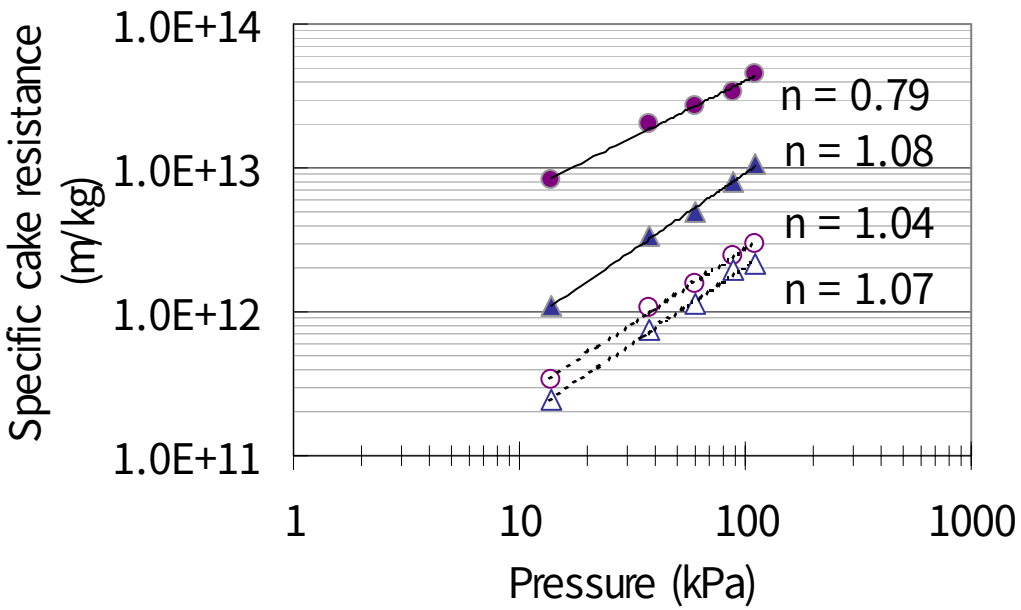
Comparison of Filtration Performance : Suspended vs.Attached



Filtration behaviors with varying MLSS concentration in attached and suspended growth MBR



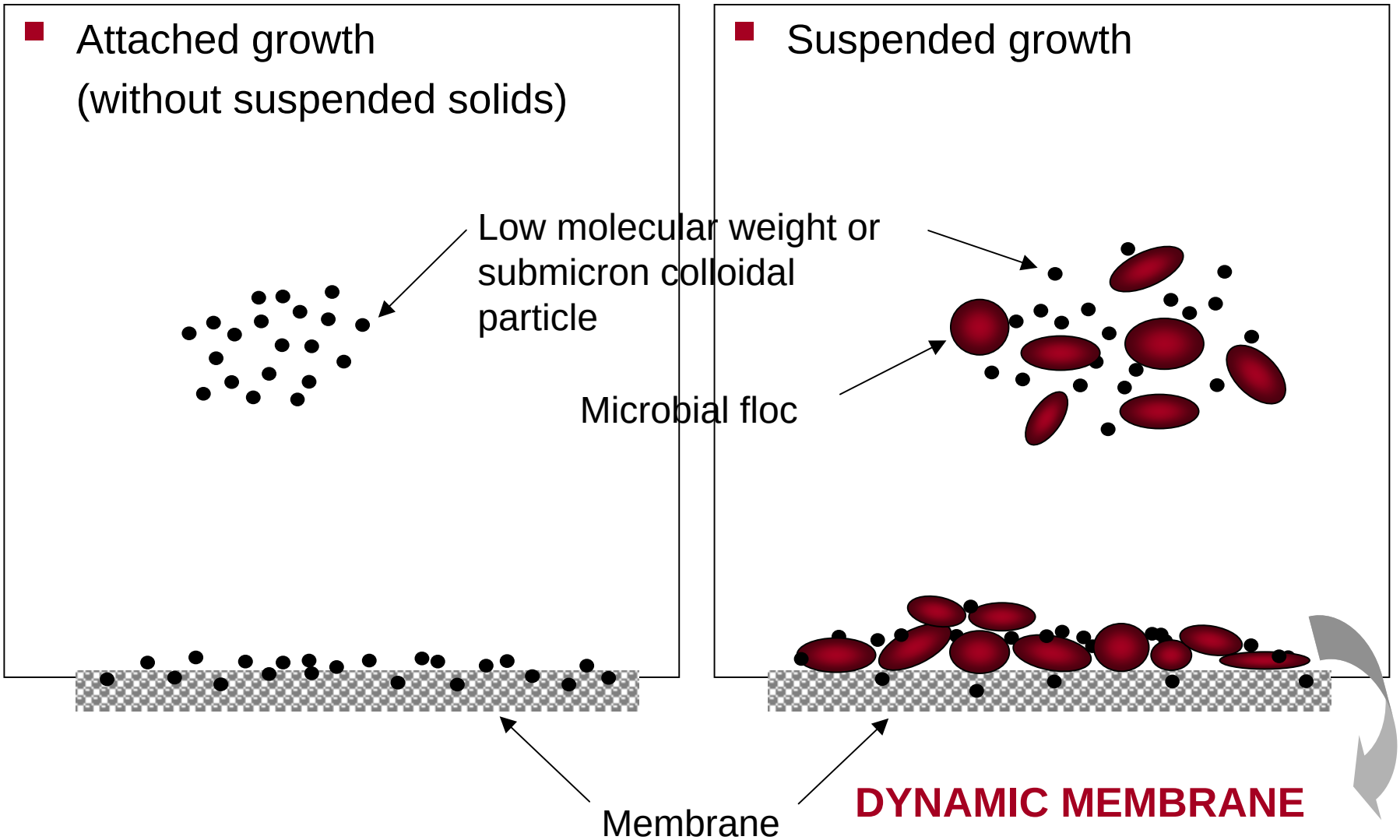
Specific Resistances of Mixed Liquors



- Attached growth
  MLSS: 100 mg/L,
  attached biomass: 2,000 mg/L
- Suspended growth
  MLSS: 3,000 mg/L
- Attached growth
  MLSS: 2,000 mg/L,
  attached biomass: 2,000 mg/L
- Suspended growth
  MLSS: 2,000 mg/L

- The mixed liquor of attached growth would have a higher fouling potential compared with that of suspended growth.
- At the same MLSS of 2,000 mg/L, mixed liquor from both attached and suspended growth revealed similar cake properties. similar filtration→behavior at the same MLSS concentration

Formation of Dynamic Membrane



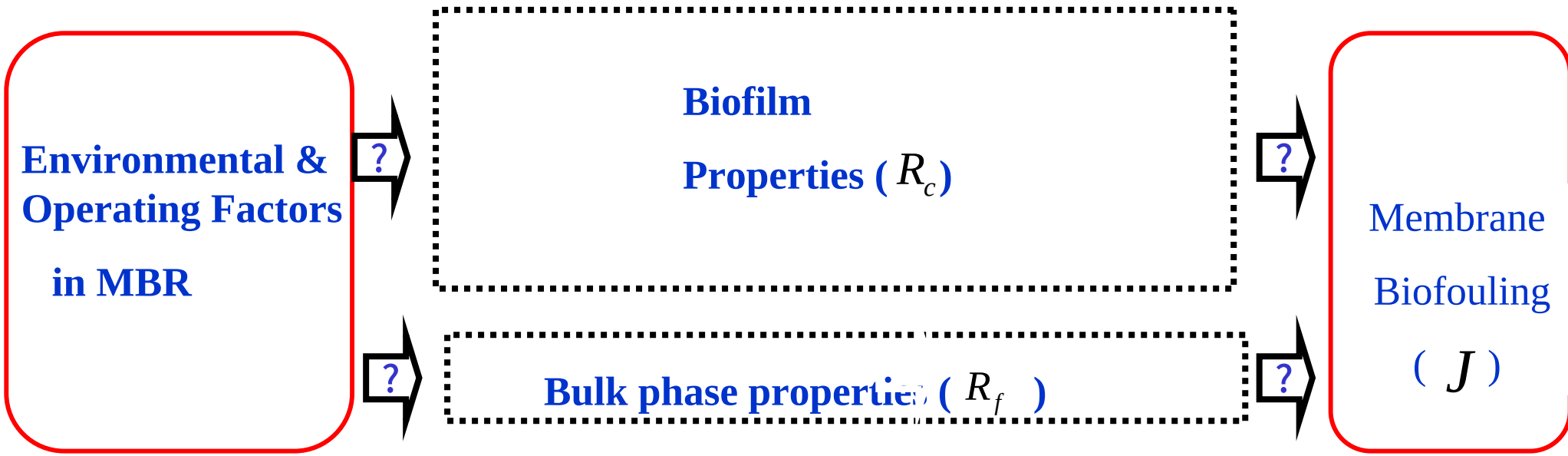
Let`s Open the Black box in MBR

Morphology of activated sludge

Hybrid system (Biological activated carbon)
Cell physiology (Growth phase)
Cell physiology (DO concentration)
Cell physiology (Cycle Format in SBR)
Cell physiology (Pump Shear)

Growth mode (Suspended vs. Attached)
✓*Conclusion and Research on MBR in 21C*

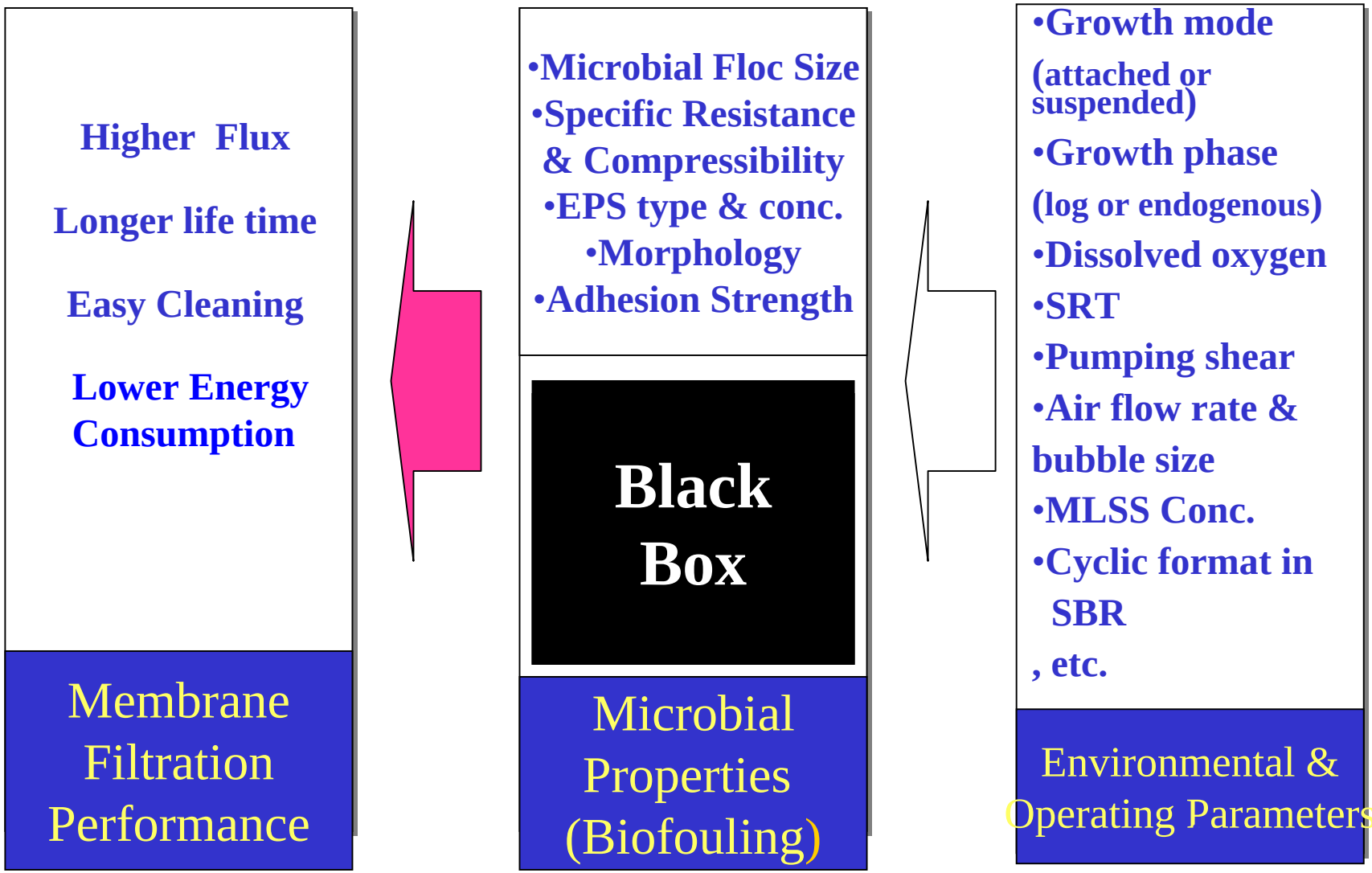
Conclusion



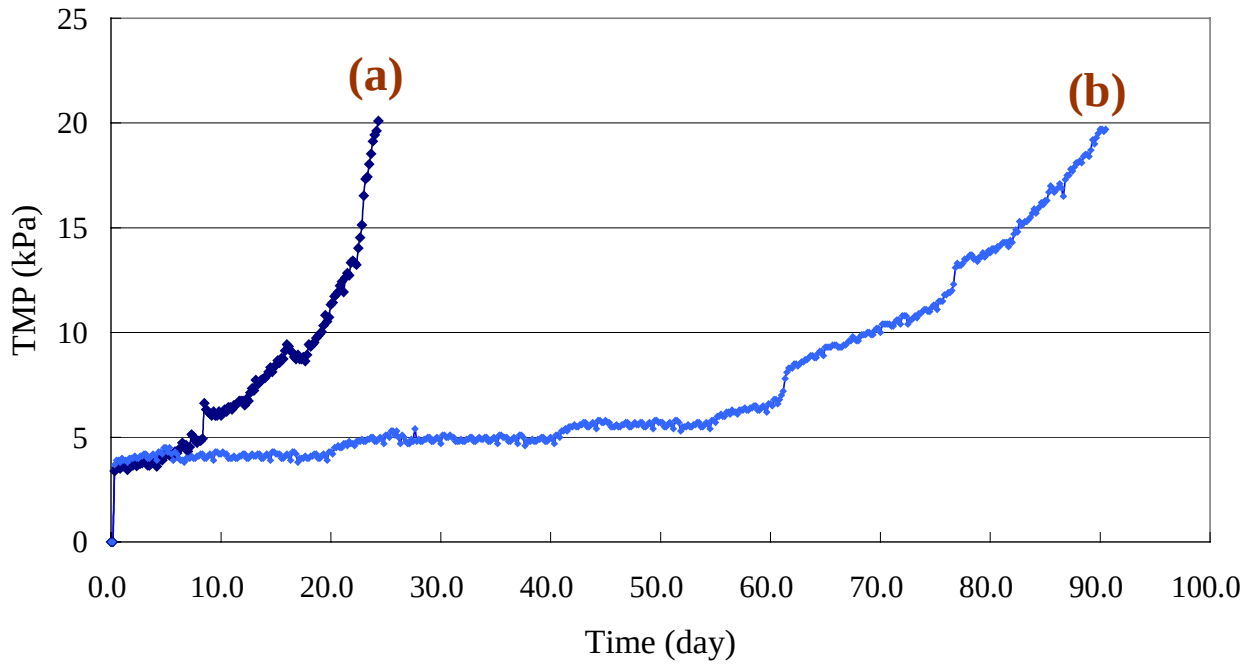
Membrane Biofouling is determined by the matrices of biofilm and bulk phase which are governed by environmental and operating factors.

The matrices of biofilm and bulk phase are in dynamic equilibrium with communities and physiology of microorganisns which are continuously changing.

Past research on MBR ?



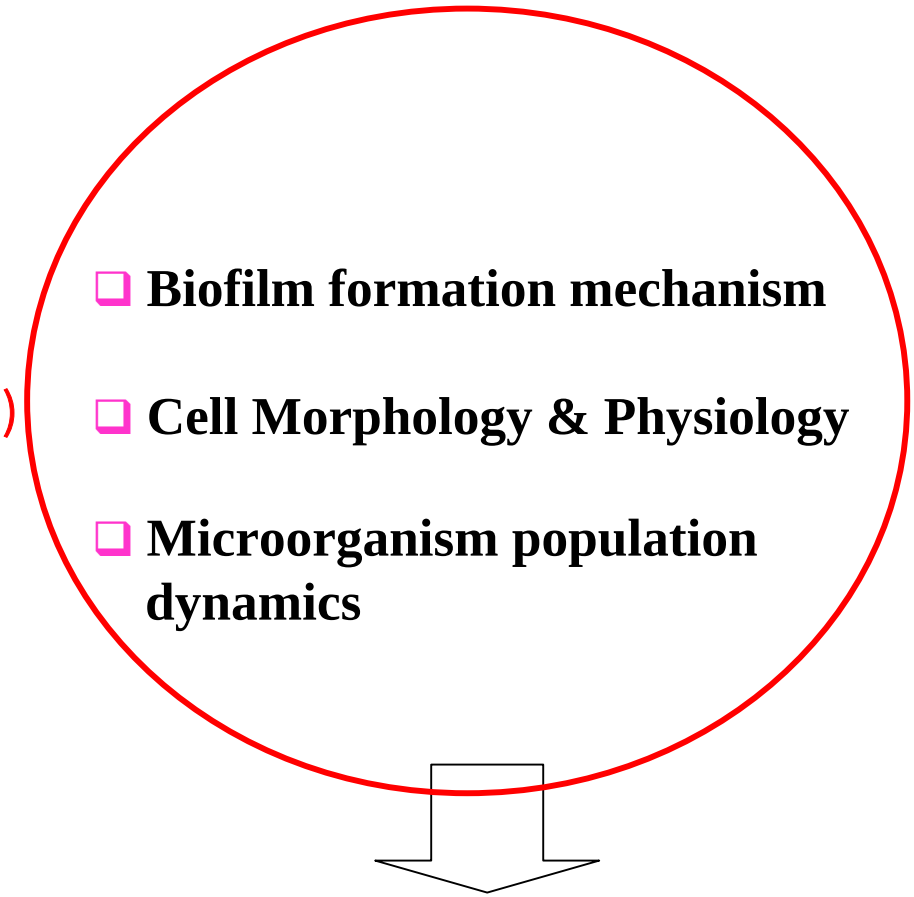
TMP profile of (a) MSBR with anoxic phase of 10 min. and (b) MSBR without anoxic phase.



	Cycle format			
	anoxic	fill	aerobic	filtration
(a)	0	10min	3hrs	50min
(b)	10min	10min	2hrs 50min	50min

Research on MBR in 21C

Using the tool of molecular biology
(FISH, PCR-DGGE, Quorum Sensing)



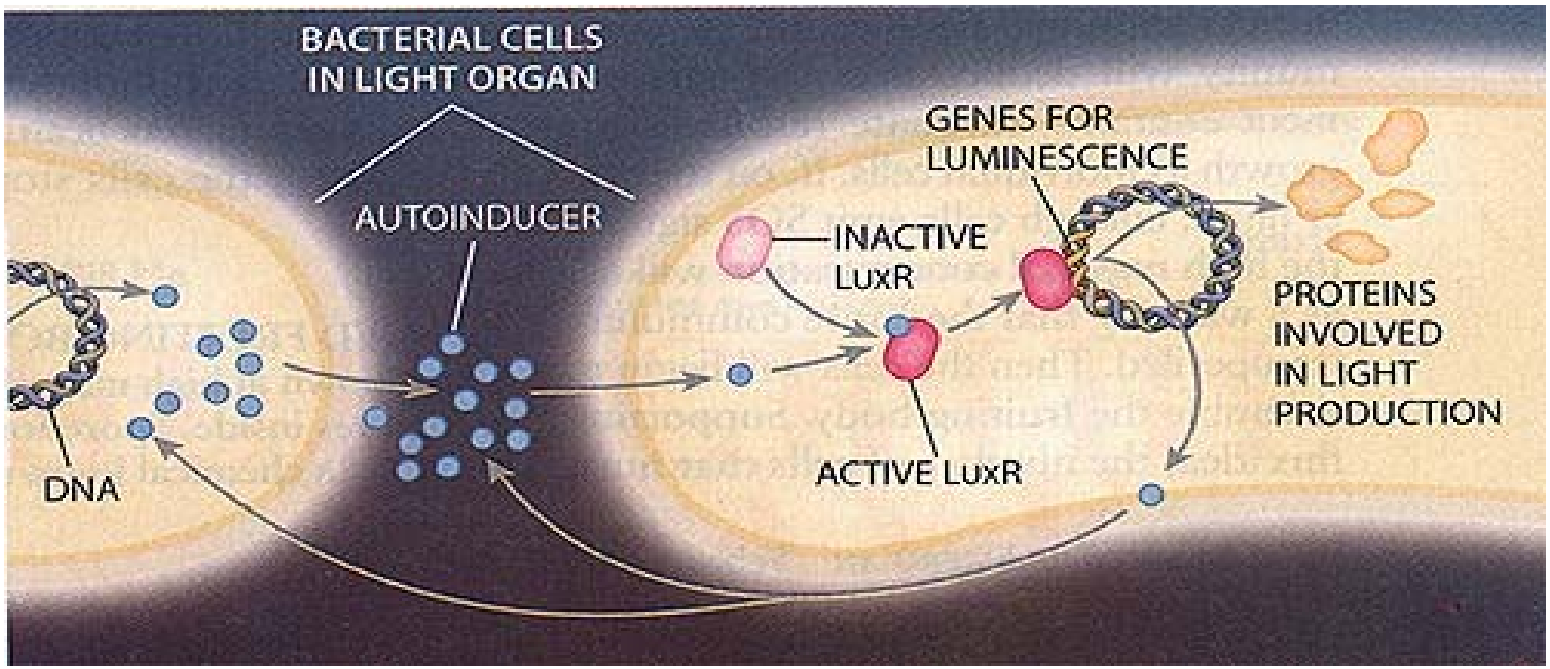
Innovative MBR process

Need for Molecular Biology to improve MBR

Molecular Biology provides high-level information which is not attainable by traditional methods:

- **Track critical groups of microorganisms**
- **Track specific metabolic reaction**

Biofilm formation mechanism:
Quorum Sensing



Autoinducer, low molecular weight, diffusible signaling molecules, can be involved in the induction of various genes that are responsible for aggregation behavior, EPS-production, disaggregation, and so on.

Biofilm formation mechanism:
Quorum Sensing

Cell-Cell communication :

Thus, cell-to-cell communication may be of fundamental importance to the dynamics of aggregation in flocs and biofilms and needs more attention in the future.

The issue is how to identify and control autoinducers involved in biofilm formation in MBR consisting of heterogeneous mixture of microorganisms instead of pure culture.

- **Thank you for your attention !!**