Fouling Characterization in Aerobic Granulation Coupled Baffled Membrane Bioreactor

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Abstract

Aerobic granular sludge treatment has been in many ways advantageous compared to other conventional aerobic wastewater treatments in terms of treatability, stronger microbial structure, high biomass retention and excellent settling ability. However, aerobic granulation is not able to produce effluent with suspended solids within standard limits. Hence, membrane filtration could be an attractive post treatment to make this process applicable. This study was conducted with the aims of treating high strength wastewater using aerobic granulation process coupled with baffled MBR and evaluating fouling potential of granulation supernatant with MBR application. The results showed that aerobic granule was able to operate at high organic loading of 15 kg COD/m^3.day with shell support media. Moreover, it was observed that soluble polysaccharides (sPS) of granulation supernatant comprised 84±18% of the soluble EPS (sEPS) which mainly caused fouling in granule MBR system.

Keywords: aerobic granule; fouling; polysaccharides; sequencing batch airlift reactor; baffled MBR.

1. Introduction

Aerobic granule has many advantages as compared with conventional activated sludge such as compactness, regularity, high bioactivity and excellent setting velocity. Settling velocity is much greater than that of conventional activated sludge (10 m/h) (Beun et al., 2002; Linlin et al., 2005), sludge volume index (SVI) is up to 12 mL/g (De Kreuk et al., 2005). Furthermore, granular sludge reactor promises a compact treatment system because of its high organic and nitrogenous loading rate. Organic loading rate (OLR) was operated more than 9 kg COD/m^3.day (Tay et al., 2003) and 15 kg COD/m^3.day (Moy et al., 2002) which is seven-fold higher as compared with conventional activated sludge process. Nitrogenous loading could be treated with loading of 1.5-16.7 kg N/m^3.day (Tsuneda et al., 2003 & 2006). The characteristics of aerobic granules are summarized in table 1.

Aerobic granules are easily formed in batch reactors after one month of operation with strong aeration and short settling time (Morgenroth et al., 1997; Beun et al., 2002). Short settling time allows granules retaining in reactor and suspended solids flowing through effluent. The suspended solids concentration in effluent depends on loading rate, settling velocity, withdrawal time, etc of the granulation system. Biomass concentration was between 75-250 mgVSS/L at loading rate of 2.5 kgCOD/m^3.day (Beun et al., 2002) and 200 mgTSS/L at loading rate of 6 kg COD/m^3.day (Arrojo et al., 2004). In fact, aerobic granulation system is not able to meet the effluent standards due to high suspended solids flowing through the effluent (De Bruin et al., 2004). Therefore coupling of aerobic granulation reactors with an aerobic baffled MBR as an attractive treatment option was investigated in this study. The purpose of this article is to determine the fouling characteristics of the granulation supernatant in baffled MBR as post treatment to granulation system.

2. Materials and Methods

2.1 Wastewater composition

In this study, glucose was used as the main organic source of synthetic wastewater for aerobic granule cultivation. The composition of wastewater is presented in table 2. When the loading rate increased, most of medium were proportionally increased with glucose concentration except micronutrients including

medium E and F. Initially, these medium were used with influent COD of 600 mg/L. Feed wastewater was maintained at pH 7.2±0.2.

Table 1. Aerobic granule characteristics

References	Substrate source	Loading ($kg/m^3.d$)	Granule diameter (mm)	SVI (mL/g)	SBC[(a)] (gVSS/L)	Reactor types	Formation time
Beun et al., 2002	Acetate	2.5	2.5	-	60	SBAR	63 days
Linlin et al., 2005[(b)]	Acetate	-	1.2	30-40	-	SBR	50 days
Tijhuis et al., 1994	Acetate	5	0.35[(c)]		15-20	BAS	-
Tay et al., 2004	Acetate	6	0.33 -0.39	46-62	40-60	SBR	21 days
Etterer & Wilderer, 2001	Acetate; glucose & peptone	3.6	1.1-6.5	-	-	SBR	56 days
Schwarzenbeck et al., 2004	Barley dust WW	3.4	2-4	30-40	-	SBR	4 weeks
Arrojo et al., 2004	Dairy WW	7	0.25-4	60	10-15	SBR	60 days
Yang et al., 2003	Ethanol	-	0.4-1.9	-	-	SBR	40 days
Wang et al., 2004	Glucose	4.8	6-9	40	-	SBR	67 days
McSwain et al., 2004	Glucose & peptone	2.4		46-114		SBR	120 days
Morgenroth et al., 1997	Molasses	2.9	2.35	-	-	SBR	40 days
Jiang et al., 2004	Phenol	2.5		40-65		SBR	-
De Kreuk et al., 2005	Sodium acetate	1.2 - 1.6	1.2	12-15	-	SBAR	48 days
Tsuneda et al., 2006	Ammonia	16.7	0.8-1.5	-	-	AUFB	100 days
This study	Glucose	2.5 - 30	0.5-4	18-35	20-62	SBAR	4 weeks

[(a)] SBC: Settled biomass concentration is amount of dry biomass per volume of settled granules after 30minutes; [(b)] Seeding sludge is anaerobic granules; [(c)] including carrier diameter d_c = 0.26 mm; WW: wastewater; SBSR: Sequencing Batch Shaking Reactor; SBR: Sequencing Batch Reactor; AUFB: Aerobic Upflow Fluidized Bed;

Table 2. Chemical components of feed wastewater

Medium	Component	Concentration (mg/L)
Medium A	Glucose	664.3
Medium B	$NaHCO_3$	450.0
Medium C	NH_4Cl	150.0
Medium D	KH_2PO_4	43.0
Medium E	$CaCl_2.2H_2O$	30.0
	$MgSO_4.7H_2O$	12.0
	$FeCl_3$	3.6
Medium F – Trace solution 1ml/L (Wang et al., 2004)	H_3BO_3 0.15 g/L; $CoCl_2.6H_2O$ 0.15 g/L; $CuSO_2.5H_2O$ 0.03 g/L; $FeCl_3.6H_2O$ 1.5 g/L; $MnCl_2.2H_2O$ 0.12 g/L; $Na_2Mo_4O_{24}.2H_2O$ 0.06 g/L; $ZnSO_4.7H_2O$ 0.12 g/L; KI 0.03 g/L;	

2.2 Support media and seed sludge

The shell carrier was produced from calciferous shell, which is made of bivalve shell of white rose cockle. The shells were dried, ground and sifted with sieve No. 70 and 100, then finally selected the size between 150-212µm. It was washed and dried again before use in the experiment. Carrier had bulk density of 1.45 g/cm^3 and weight loss of 2% at 550°C, 20 minutes. Initially, amount of carrier added was 50g (20 g/L) and 10 g was added each month for compensating for the loss through sampling and effluent discharge. Seed sludge was taken from conventional activated sludge process and the system was started with initial MLSS concentration of 6 g/L. This sludge had SVI of 243 mL/g and hydrophobicity of 31%.

2.3 Reactor configuration and operating conditions

The experimental set up is presented in Figure 1 including SBAR, similar to Beun et al. (2002) and baffled MBR for shell granule cultivation and filtration, respectively. In SBAR, air was introduced by a fine bubble aerator at the bottom of the reactor at a superficial air velocity of 95 m/h (air flow rate of 4.5 L/min). The SBAR is operated in 3-hour cycle, consisted of 5 minutes influent feeding, 170 minutes

aeration, 3 minutes settling, and 2 minutes effluent withdrawal. Supernatant from SBAR is discharged into aerobic baffled MBR by the effluent valve. All the cycles is controlled automatically by PLC system.

Aerobic baffled MBR which was operated continuously had two settling compartments and one membrane compartment. Settleable solids are settled in two first chambers. Flatsheet microfiltration membrane is inserted into last chamber to produce high quality permeate. Vertical flow in baffled reactor allows suspended solid settled and retained in sludge hopper. Sludge is withdrawn twice with total volume of 500 mL/day. Unsettled colloids and particles passed through these baffles and rejected by membrane filtration in the last chamber. In membrane compartment, air is supplied through air diffuser to reduce cake layer formation on membrane surface for fouling control. Membrane pore size is 0.1 µm.

Table 3. Operating conditions of aerobic granule coupled baffled membrane bioreactor

Parameters	SBAR	Aerobic baffle MBR
Working volume	2.5 L	8.5 L
Organic loading rate	2.5 – 30 kgCOD/m^3.day	-
Air supply	95 m^3/m^2/h (4.5 L/min)	6 m^3/m^2/h (1 L/min)
HRT	5.8 h	12 h
Operation mode	Batch, 3 h	Intermittent suction
Membrane surface area (6cm x 11cm), PVDF 0.1 µm		66 cm^2
Filtration rate (8 minute on/4 minute off)		27 L/m^2.h

2.4 Analytical methods

Membrane fouling index (MFI) was measured by the slope of time versus time/volume (s/L^2) with flat sheet cellulose acetate membrane 0.2 µm at pressure of 1 bar by stirred cell made by Germany. Membrane resistance was measured as the method of Choo and Lee (1996). Particle size distribution of mixed liquor in membrane chamber was determined by Mastersizer S (Malvern, UK). Extracellular polymeric substances (EPS) in terms of polysaccharides (PS) and protein (PN) were analyzed by the methods of Dubois, et al. (1956) and Lowry et al. (1951), respectively. COD, MLSS, SVI, SOUR were according to APHA et al. (1998). Biomass in term of MLVSS was determined by measuring TOC of sonicated granule sample. Then TOC was converted to MLVSS by factor 2.05 as combined method of Tijhuis et al. (1994) and Beun et al. (2002). The relative cell hydrophobicity of sludge was measured as adherence to hexadecane as mentioned by Jin et al. (2003).

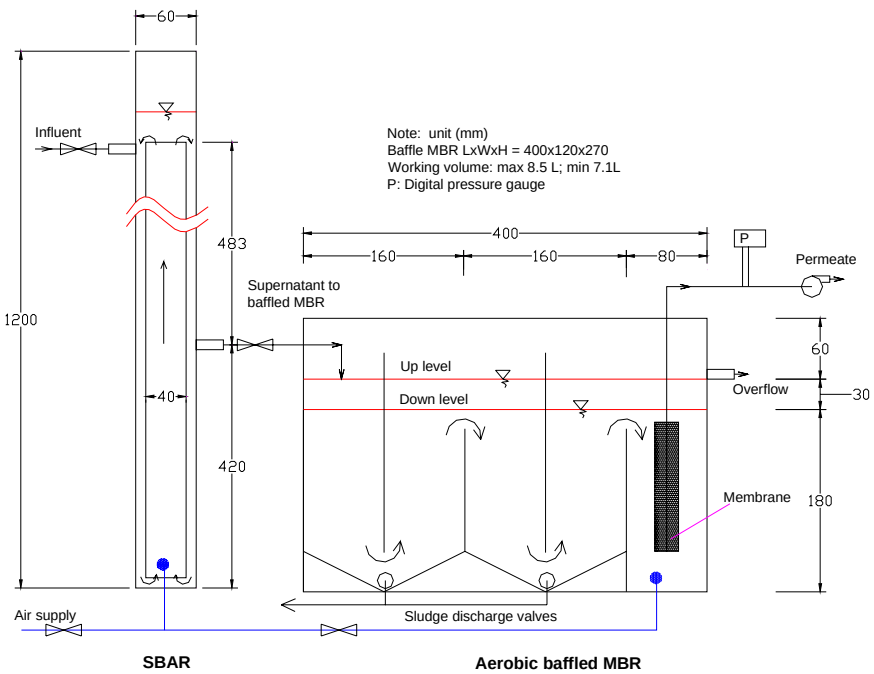
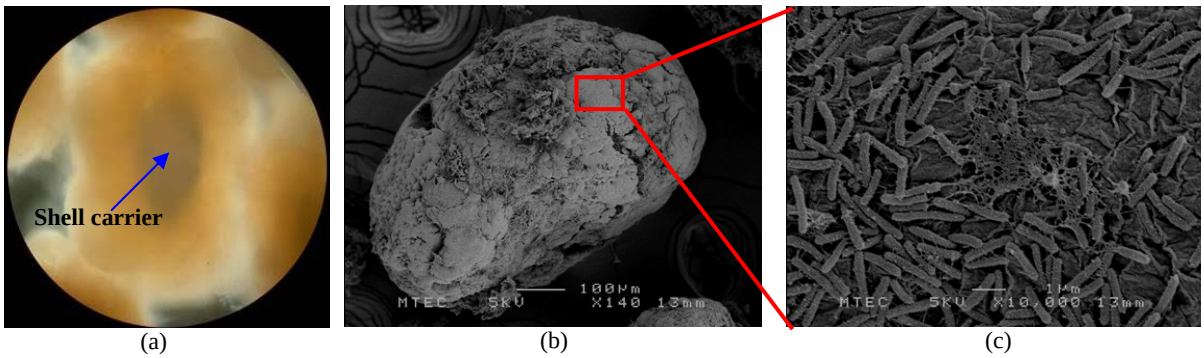


Figure 1. Aerobic granulation coupled baffled membrane bioreactor

3. Results

3.1 Shell granule characteristics

Matured shell carrier granules were formed after 4 weeks of operation at OLR of 2.5 kgCOD/m^3.day. When granule formed, sludge characteristics also changed significantly in terms of particle size, sludge settling, compactness, hydrophobicity, etc. Shell granule had size in range of 0.1-2.0 mm, SVI of 18-30 mL/g, settled biomass density of 25–49 g/L$_{granular\ sludge}$, hydrophobicity of 51-81% for all loading rates from 2.5-30 kgCOD/m^3.day. In addition, the surface of shell granules also contained majority of rod-shape like bacteria and cross-linked materials similar to Tay et al. (2001) and other authors in previous research. Typical shell granules were taken by light and scanning electron microscopes as presented in figure 2.



(a) (b) (c)

Figure 2. Morphology of matured shell granule. (a) taken by light microscope x20; (b,c) taken by Scanning electron microscope

3.2 Treatment efficiency of SBAR with aerobic shell granules

The SBAR could operate up to 30 kg COD/m^3.day with organic treatment efficiency greater than 96% for all loading rates (Figure 3). Organic matters were biodegraded or absorbed by granules within ten minutes of initial aeration. Other authors also achieved high organic loading in granulation systems such as 9 kg COD/m^3.day (Tay et al., 2003), 15 kg COD/m^3.day (Moy et al. 2002). The SOUR was found to be 46.7 mgO_2/gVSS.h for aerobic shell granules reflecting high bioactivity. This value is almost three-fold greater than conventional activated sludge. Bioactivity of different types of sludge is showed in table 4. When characterizing fouling potential of granulation supernatant organic loading was limited at 15 kgCOD/m^3.day. During the operation the system was usually clogged at the greater loading rates. In this case, it was due to high viscosity of mixed liquor and large granules getting clogged between the walls of the airlift reactor. However, in practice the loading was also limited at 10-15 kgCOD/m^3.day for membrane bioreactors or any aerobic unit processes because of the deficiency of oxygen transfer. Oxygen transfer efficiency is highly dependent on MLSS or biomass concentration. High MLSS causes reduction in oxygen transfer. Yoon et al. (2004) reported that specific oxygen transfer efficiency reduced 50% when MLSS increased from 5,000 to 10,000 mg/L. In granulation systems or MBRs, MLSS are usually very high (greater than 10,000 mg/L).

Table 4. Specific oxygen uptake rate (SOUR) of kinds of sludge

Sludge	Shell granule	Granule	Granule	Granule	Granule	Activated Sludge
SOUR, mg/gVSS.h	46.7	69.4	96.5mg/gSS.h	95	41.9	18.3
Reference	This study	Tay et al., 2001	Morgenroth et al., 1997	Qin and Liu, 2006	Liu et al., 2005	

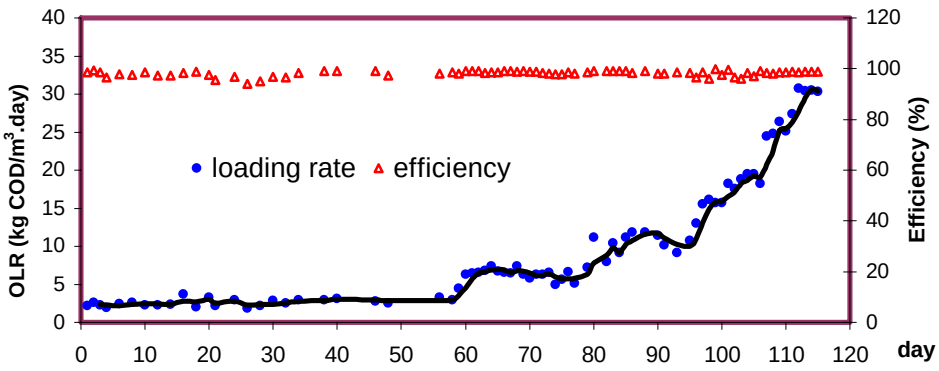


Figure 3. Treatment performance of SBAR with aerobic shell granules

3.3 Variation of MLSS in baffled MBR

In figure 4, suspended solids found in the settling and membrane chamber of baffled membrane bioreactor ranged from 78 to100 mg/L and 40-65 mg/L respectively at varying loading rates. There was very low soluble COD in bulk liquid of SBAR supernatant indicating low soluble substrate in baffled MBR. The loss of biomass in membrane chamber was due to their biodegradation by aeration, where microorganisms were always in endogenous condition. The amount of biomass reduction due to aeration in membrane chamber was from 34.0 to 48.7% at various loading rates.

Even though MLSS in the MBR chamber is less than that in the settling chamber, the MFI of mixed liquor in the MBR chamber was 29% higher than that of the supernatant from SBAR. This could be explained by the lysis of colloids and cells occurring in membrane chamber. The cell lysis could be responsible for high soluble microbial products and in particular high PS concentration in membrane chamber.

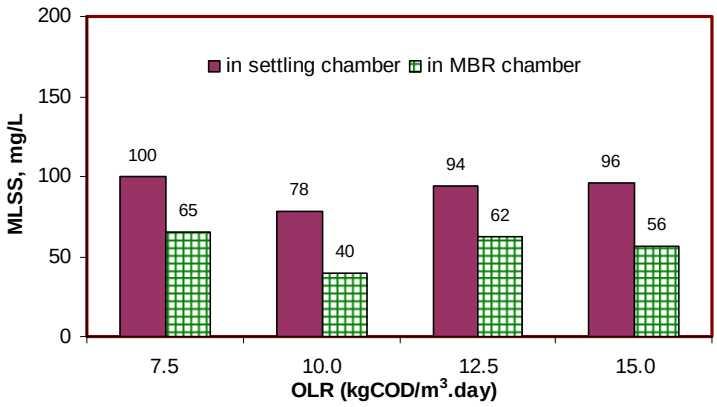


Figure 4. MLSS in effluent of SBAR, settling chamber and membrane chamber

3.4 Soluble microbial products and its fouling correlation

As the OLR increases, the sEPS of granulation's supernatant also boosts which mostly comprised of sPS (84±18%). sEPS of granulation's supernatant was very different as compared with that of MBR. In MBR, soluble protein was usually dominant or equal with sPS in sEPS. This study shows that the microorganism in granular sludge secretes more soluble polysaccharides compounds than proteinaceous ones as shown in Figure 5. This means PS plays an important role in membrane fouling. Fouling potential of granule supernatant in term of membrane fouling index was very much correlated with soluble EPS, especially with soluble PS as shown in Figure 6. Rogenberger et al. (2006) found that fouling rate was

proportional to PS concentration in filtered mixed liquor of MBR when the sludge is 8 days old. Thus, it could be concluded that PS causes membrane fouling in granulation's supernatant and its fouling effect is similar to that of submerged MBR's supernatant.

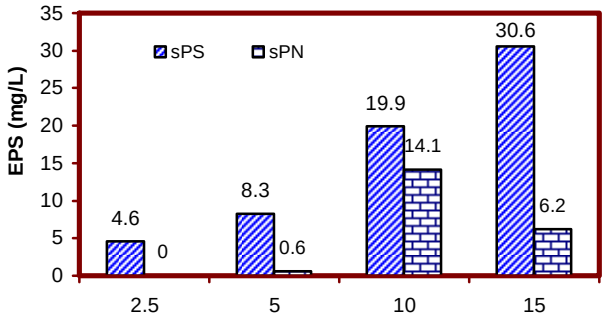


Figure 5. Soluble EPS at varying OLRs (kgCOD/m^3.d)

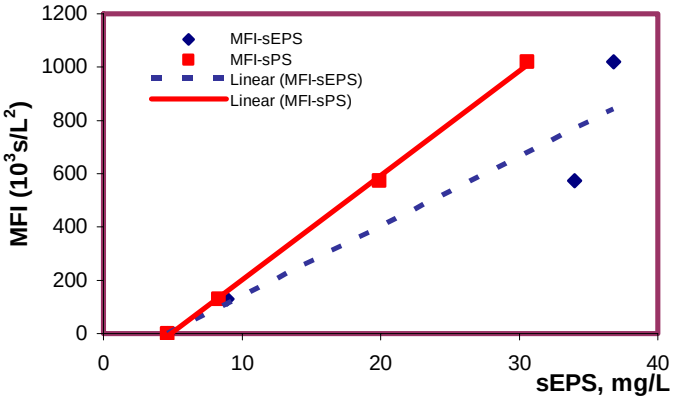


Figure 6. Correlation between soluble EPS and fouling potential

3.5 Fouling mechanism in aerobic granulation coupled baffled membrane bioreactor

Most of the solids were settled in settling chamber while the remaining unsettled particles, colloids and solutes flow to the MBR chamber for further filtration. The mean size of particles found in MBR chamber was 95.8 µm and the minimum size was greater than 0.3 µm (membrane pore size of 0.1 µm) (figure 8). Particles/colloids which are unable to pass through the membrane due to its large size are deposited on the membrane, thus forming a thin biofilm layer on membrane surface. It can be observed during system operation. In addition, a component of EPS, mainly PS is deposited and adsorbed on membrane surface and pores causing membrane fouling. During operation, soluble PS was stable at 30.8±0.8, 18.3±0.3 and 3.0±0.2 for SBAR supernatant, bulk liquid in MBR and permeate respectively. It indicates that soluble PS degradation in MBR chamber, deposit on membrane and passing through permeate was 40.6, 49.7 and 9.7% respectively.

Figure 7 shows percentage of different particle sizes in mixed liquor and mean diameter of particles. The results show that the average size of particles is generally greater than the pore size of membrane (0.1 µm). In addition, fouling occurred when particles were deposited on the surface (surface deposition) results in "cake layer" formation. In this experiment, "cake layer" in actual fact was a thin biofilm layer which could be observed on flatsheet membrane surface. This contributes to fouling and can be reflected by "cake resistance" value (table 5).

Table 5. Membrane resistances

Items	Resistance (m^{-1})	Percentage (%)
Total resistance (R_T)	$3.156*10^{12}$	
Intrinsic resistance (R_m)	$0.123*10^{12}$	4
Cake layer resistance (R_c)	$1.179*10^{12}$	37
Irreversible resistance (R_f)	$1.852*10^{12}$	59

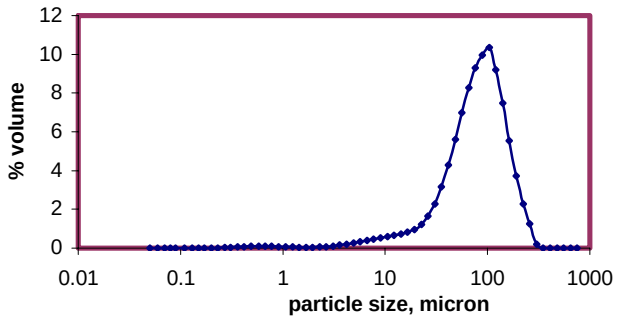


Figure 7. Particle size distribution of mixed liquor in membrane chamber at OLR of 15 kgCOD/m^3.day

Furthermore, results from membrane resistance measurement indicates that irreversible fouling mainly contributes to fouling of membrane (59%) (table 5). "Cake layer" or thin biofilm resistance only adds up to 37% of total resistance. Finally, this study illustrates that fouling of granulation's supernatant is due to polysaccharides deposition on membrane which caused irreversible fouling.

4. Conclusions

In this study, fouling characterization of aerobic granular sludge coupled baffled membrane bioreactor was investigated at varying loading rates. The following conclusions could be drawn:

(a) Shell carrier could be used as support media for aerobic granule cultivation.
(b) Shell granule coupled MBR could operate at high organic loading up to 15 kg COD/m^3.day.
(c) Soluble polysaccharides in supernatant of granulation system comprising of 84±18% of soluble EPS increases with organic loading rate. It was identified to be the key fouling factor in aerobic granulation coupled baffled membrane bioreactor. The fouling behavior of granulation's supernatant due to soluble Polysaccharides, is somehow similar to that of mixed liquor in submerged MBR.
(d) Fouling potential increases linearly with soluble polysaccharides existing in supernatant from granulation process. As a result of deposition of polysaccharides on membrane surface as well as membrane pores, Polysaccharides is identified to be the source of irreversible fouling.

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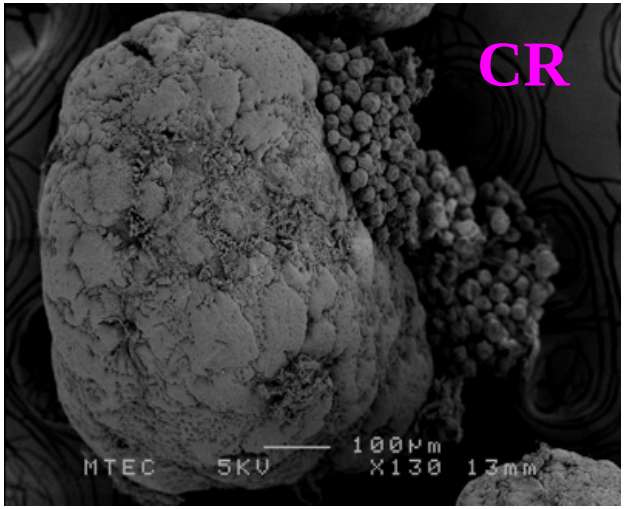

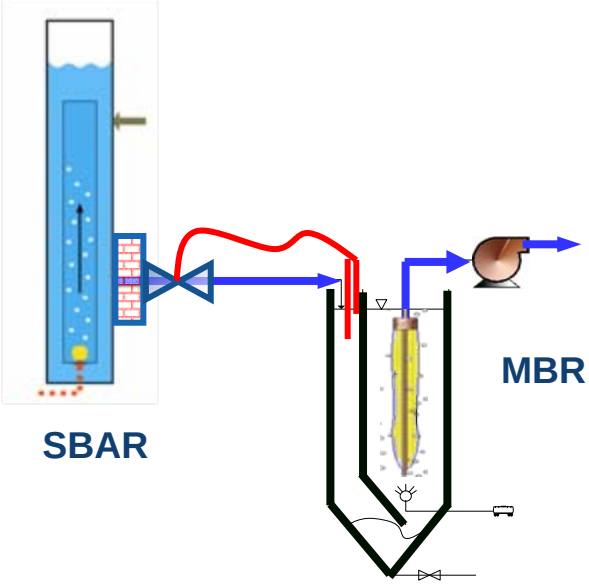

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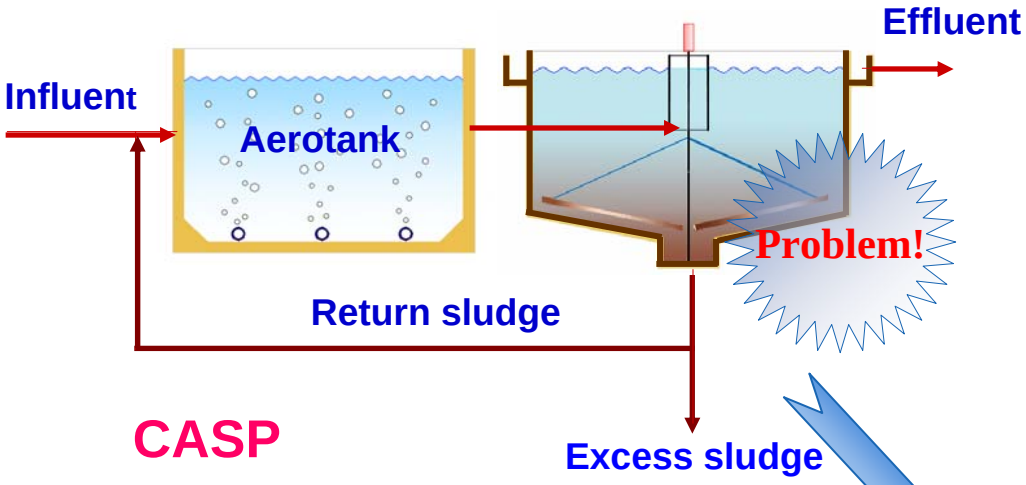
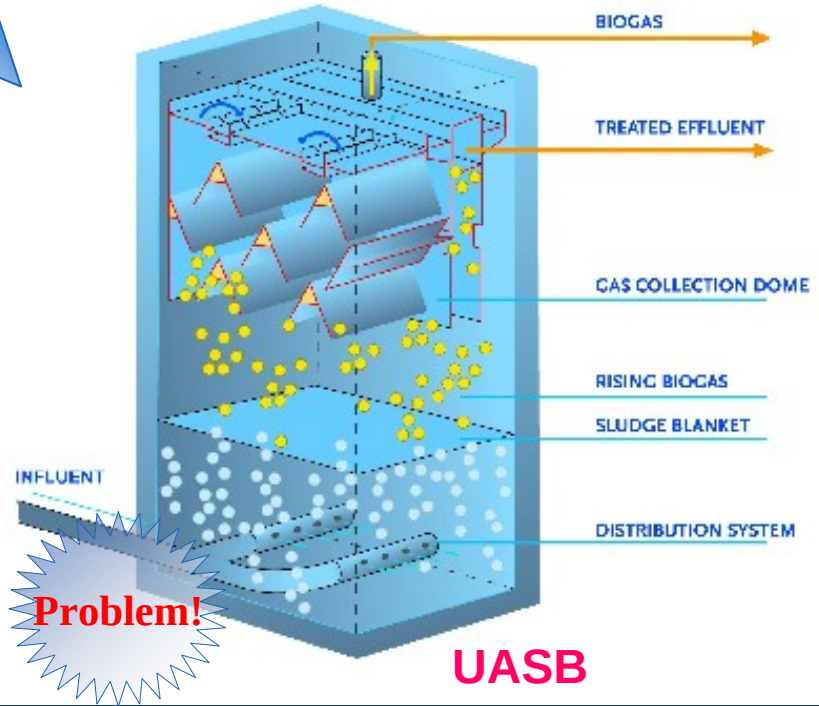


CASP

Conventional Activated Sludge:
Aerobic process;
Popular for all current plants;
Low OLR (< 2 kgCOD/m^3.d);
Low biomass retention;
Effluent quality (SS>30 mg/L);
Settling velocity < 10 m/h;
Floc size < 0.9 mm

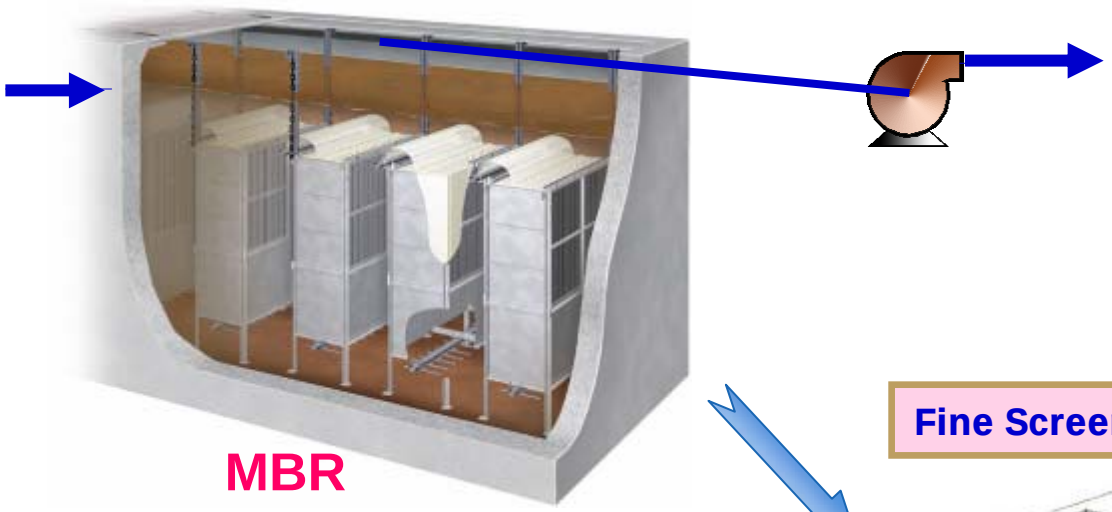
Anaerobic Process (Lettinga, 1980):
High OLR up to 40 kgCOD/m^3.d;
Applied for high strength WW;
High biomass retention (10-40 kg/m$^{3)}$;
May form anaerobic granules;
Produce value biogas;

Obstacles:
But need to combine with CASP;
Difficult O & M;
Scaling, acclimatization, etc

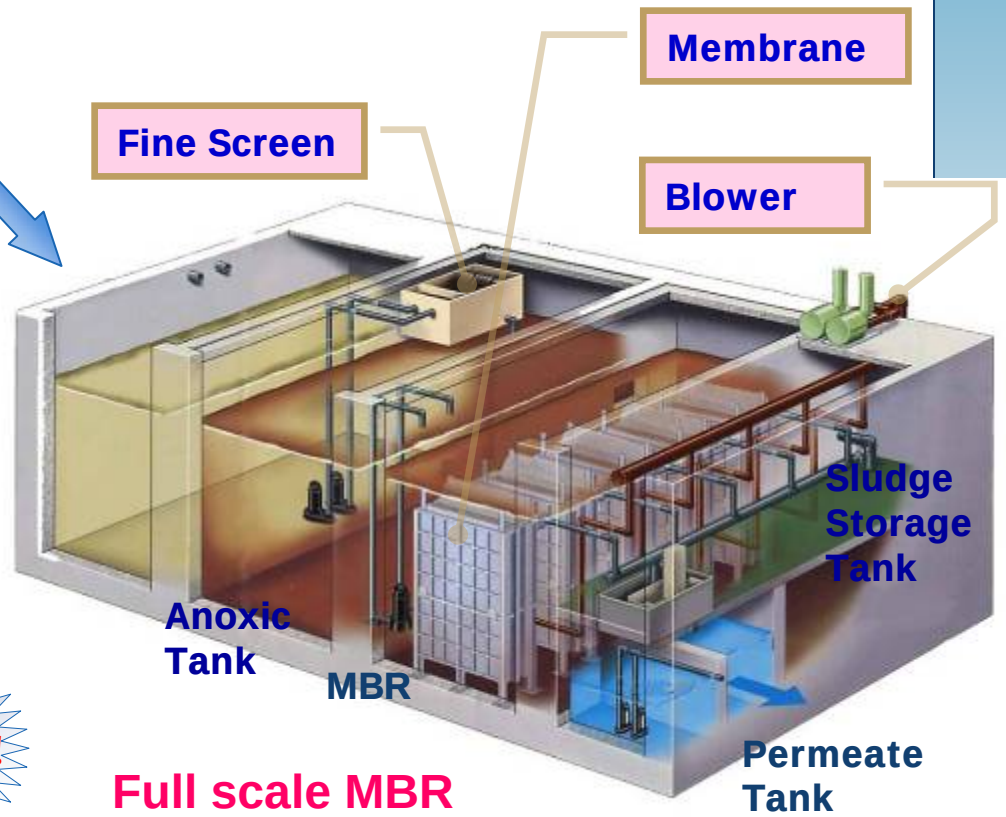


UASB

Background



MBR



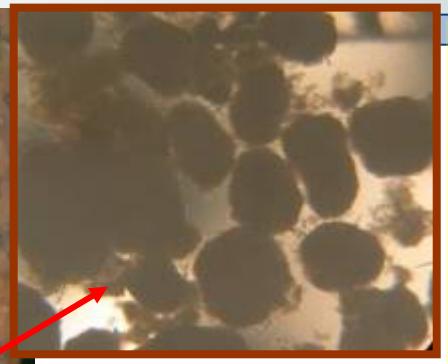
Full scale MBR

Submerged MBR (Yamamoto, 1989):
Being popular due to cost reduction
Water reuse and recycling;
High SRT, OLR;
Less footprint;

But sludge treatment difficult
Fouling, oxygen transfer

Problem!

Aerobic Granule and MBR



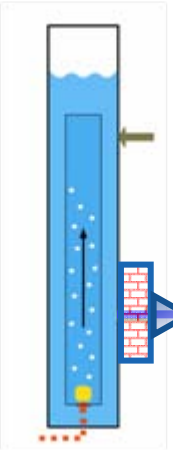
Aerobic Granules (Tjihuis, 1994):
- Recent Research success
- Regular, spherical structures
- High OLR up to 30kg COD/m^3/d ;
- High SRT due to compactness;
- Excellent settling (SVI = 18mL/g);
- Less footprint;
- Nitrification/Denitrification;
- Toxic substance tolerant;

Problem!

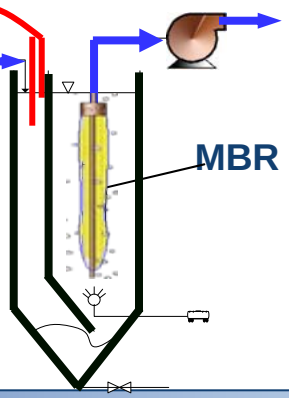
But high SS in effluent:
[75-250 mg/L(Beun et al., 2002); 200 mg/L (Arrojo et al., 2004)]

High aeration cost.

Why not combine AEROBIC GRANULE & MBR?



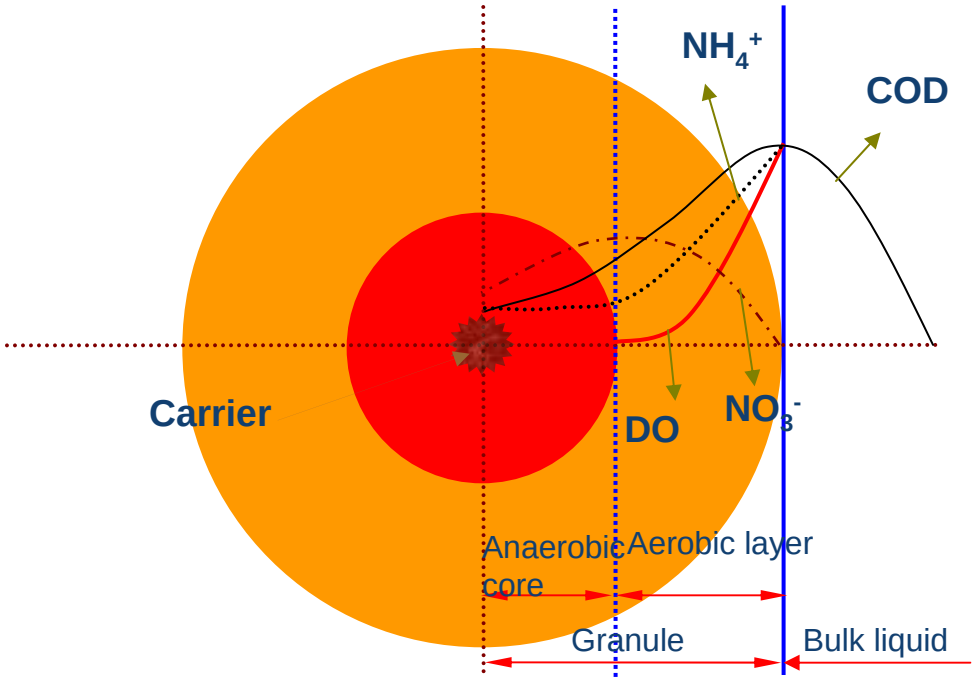
SBAR



Advantages of Aerobic Granule

Granular Sludge:

- Can operate stability at the cool temperature (8°C) *(De Kreuk et al., 2005)* ;
- Can happen simultaneous nitrification and denitrification *(Qin et al., 2005)*;
- Involve diversity of microbial population;
- Can remove recalcitrant: phenol (3.8 kg/m^3.day) *(Tay et al., 2005)* and nitrilotriacetic (NTA) *(Nancharaiah et al., 2006)*



Conventional Act. Sludge:

- Fluffy
- Irregular
- Loose structured morphology

Aerobic Granule Characteristics

References	Substrate source	Loading ($kg/m^3.d$)	Diameter (mm)	SVI (mL/g)	SBC[a] (gVSS/L)	Reactor	Formation time
Beun, 2002	Acetate	2.5	2.5	-	60	SBAR	63 days
Linlin, 2005[b]	Acetate	-	1.2	30-40	-	SBR	50 days
Tijhuis, 1994	Acetate	5	0.35[c]		15-20	BAS	-
Tay, 2004	Acetate	6	0.33 -0.39	46-62	40-60	SBR	21 days
Etterer & Wilderer, 2001	Acetate; glucose & peptone	3.6	1.1-6.5	-	-	SBR	56 days
Schwarzenbeck, 2004	Barley dust WW	3.4	2-4	30-40	-	SBR	4 weeks
Arrojo, 2004	Dairy WW	7	0.25-4	60	10-15	SBR	60 days
Yang, 2003	Ethanol	-	0.4-1.9	-	-	SBR	40 days
Wang, 2004	Glucose	4.8	6-9	40	-	SBR	67 days
McSwain, 2004	Glucose & peptone	2.4		46-114		SBR	120 days
Morgenroth, 1997	Molasses	2.9	2.35	-	-	SBR	40 days
Jiang, 2004	Phenol	2.5		40-65		SBR	-
De Kreuk, 2005	Sodium acetate	1.2 - 1.6	1.2	12-15	-	SBAR	48 days
Tsuneda, 2006	Ammonia	16.7	0.8-1.5	-	-	AUFB	100 days
This study	Glucose	2.5 - 30	0.5-4	18-35	20-62	SBAR	4 weeks

Aerobic granule can form with any WW sources, any batch reactor, about 1 month, and excellent setlling characteristic.

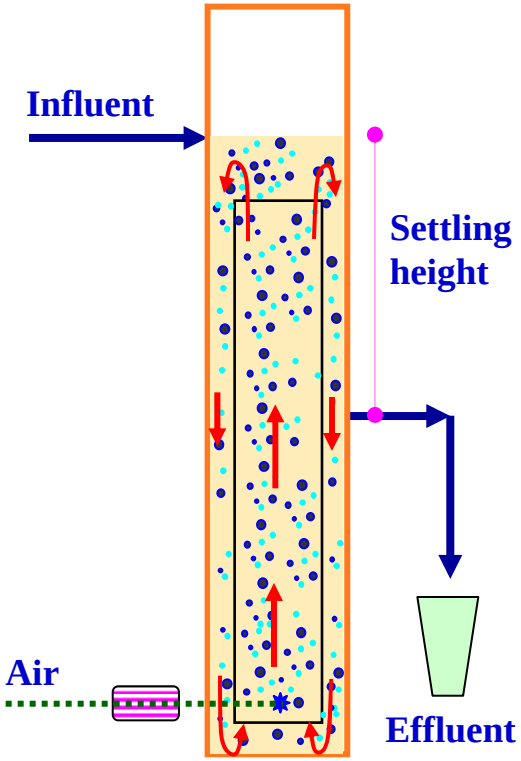
Objectives of Study

1. Characterize effluent characteristics from SBAR as a base for membrane combination;

2. Characterization of fouling potential of granulation supernatant with aerobic baffled MBR.

Experimental Set-up & Operation

Run 1: OLR =2.5

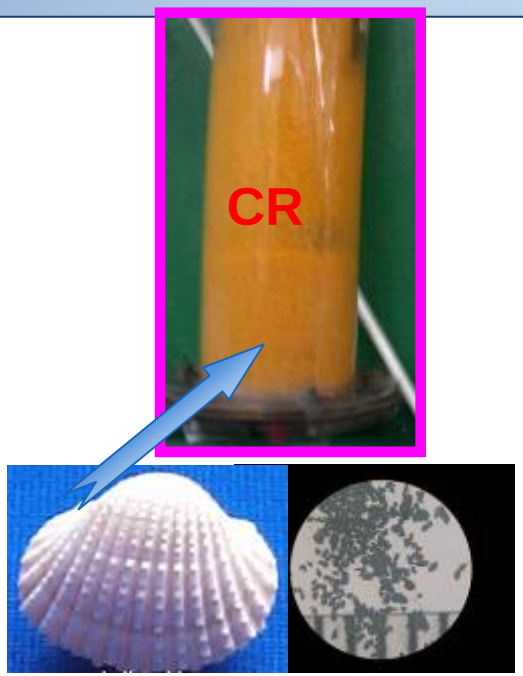


SBAR:

V = 2.5 L

D = 6 cm

H = 120 cm;

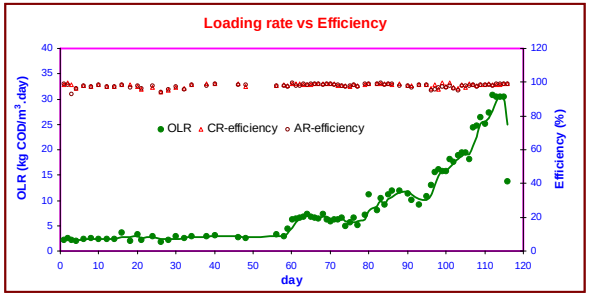


Bivalve shell Carrier

Operated with 4 stages:

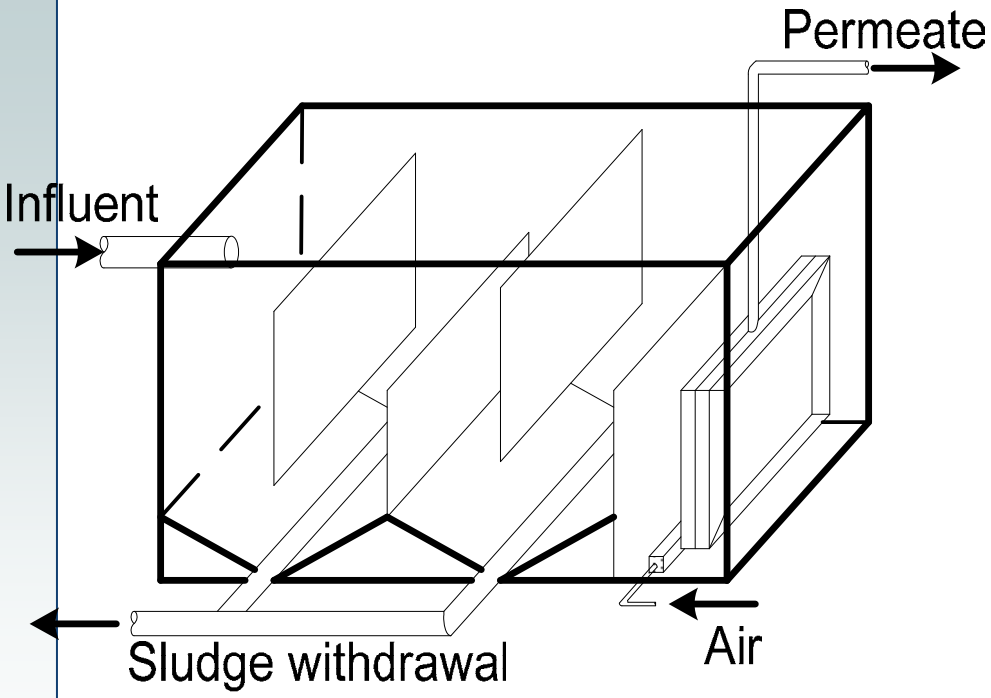
- **Fill : 5 min**
- **Aeration: 170 min, v = 95 m/h)**
- **Settling: 3 min (v_s > 10 m/h)**
- **Withdrawal: 2 min**

Run 2: OLR = 5; 10; 30



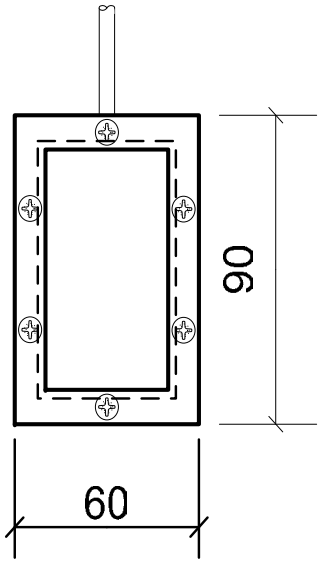
Baffled Reactor

Baffled Membrane Bioreactor:



Flat sheet, PVDF 0.1 µm

Membrane area: 6 x 11 (cm)



L x W x H: 400 x 120 x 170 (mm)

Total volume: 8.5 L

Sludge hopper: 1.5 L

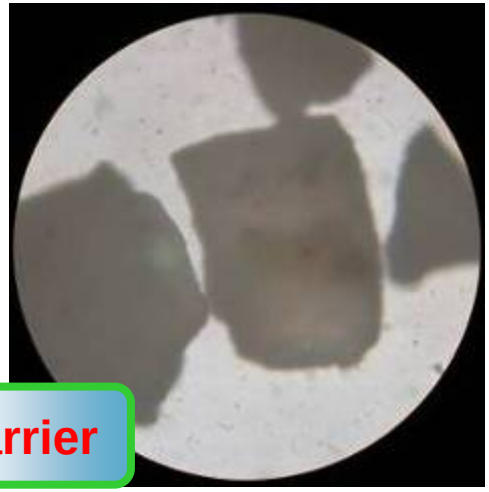
Air supply : 6 $m^3/(m^2.h)$

Intermittent suction: 8 min on/4 min off

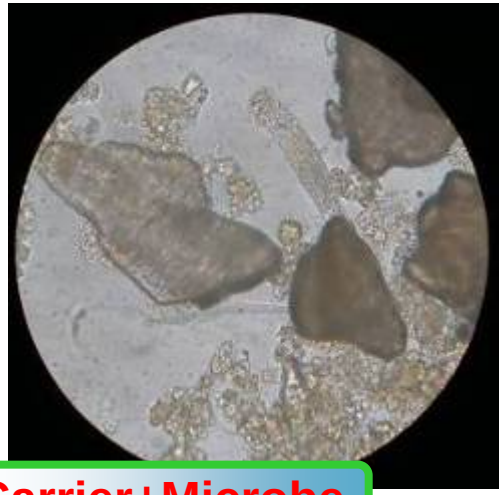
Flux: 27 $L/(m^2.h)$

Shell Granule Development

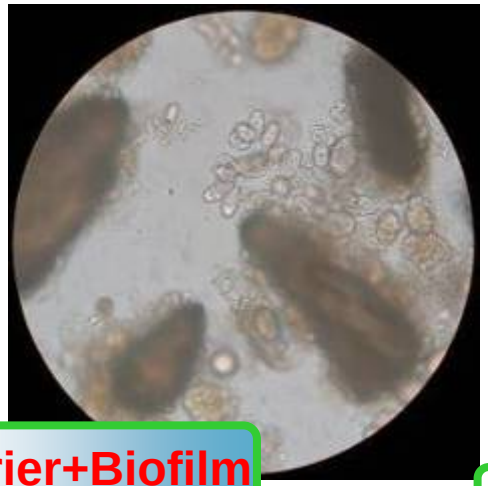
Conventional AS



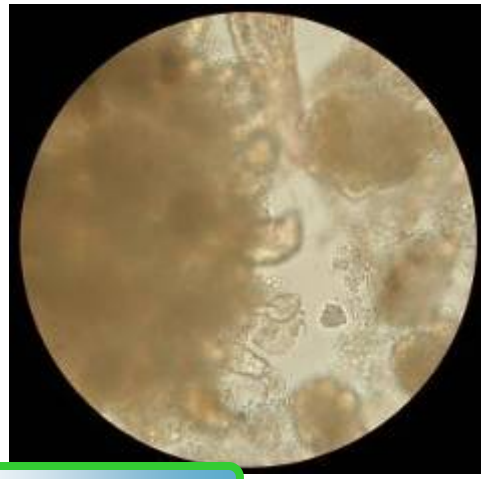
Carrier



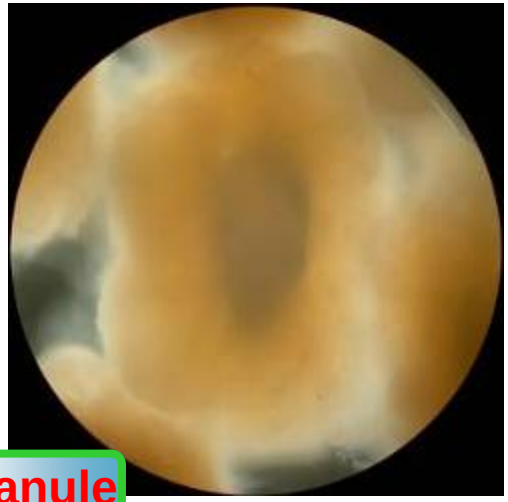
Carrier+Microbe



Carrier+Biofilm

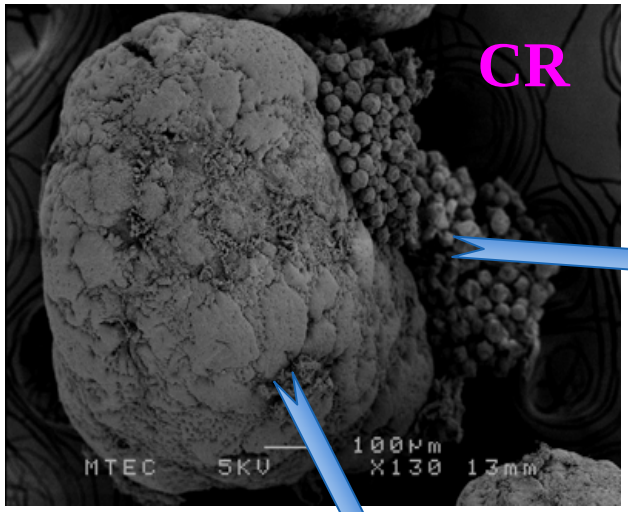


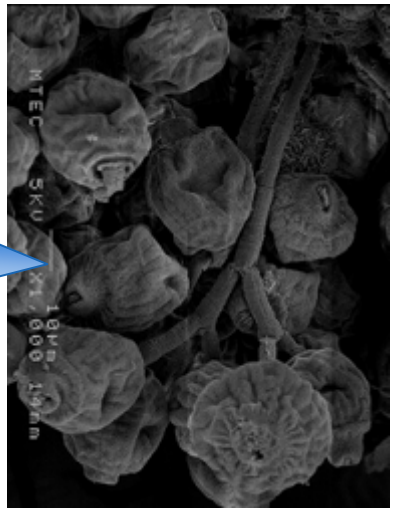
Initial granule



Granule

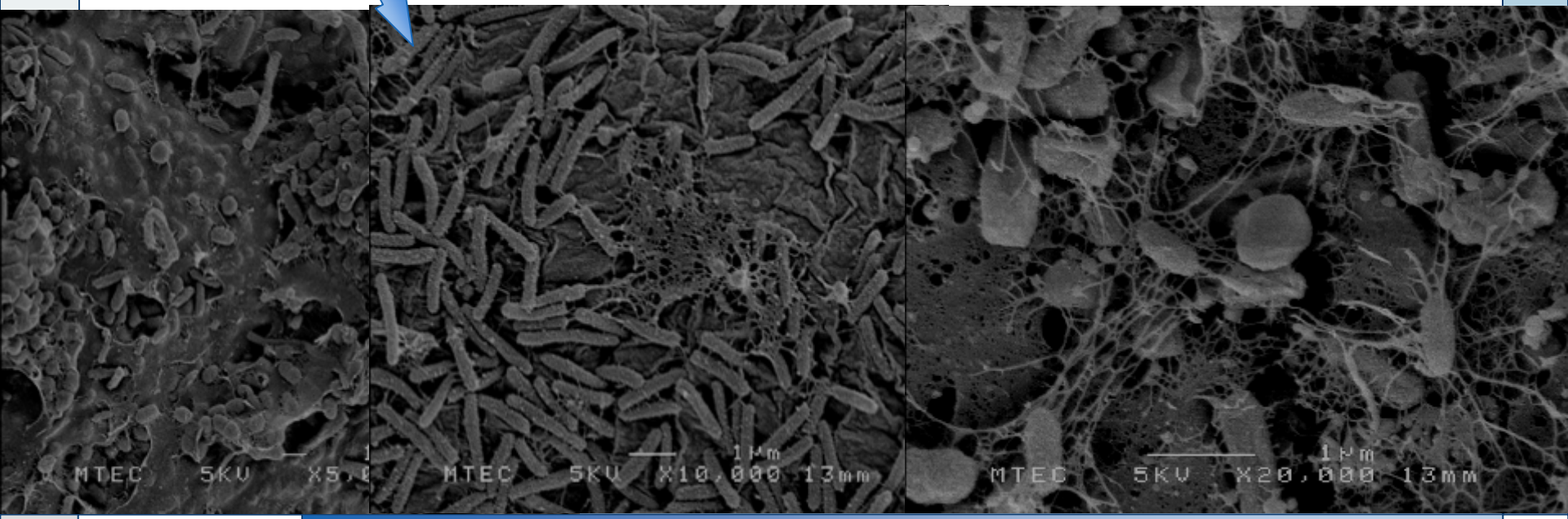
Shell Granule Morphology



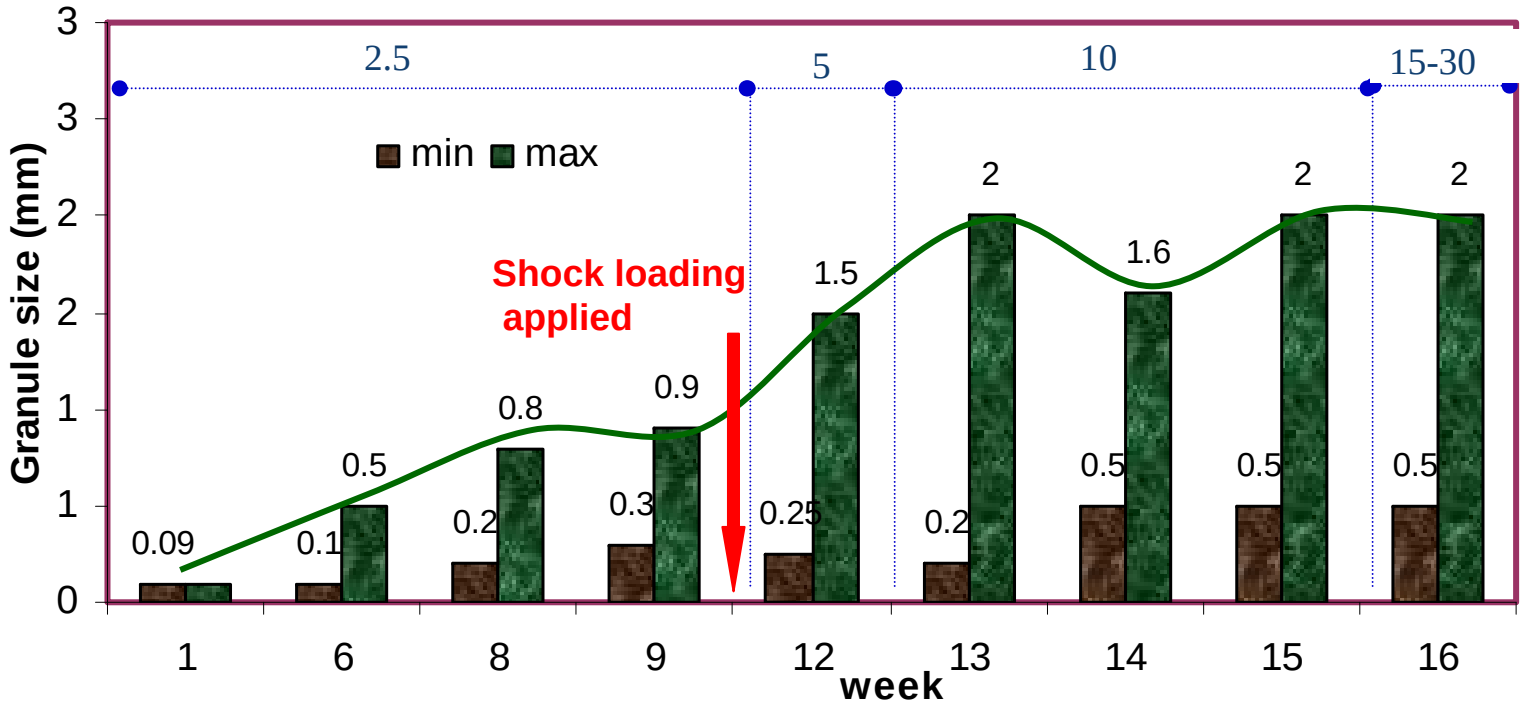


Morphology - SEM

Rod-shape, Cocci type bacteria and fungi

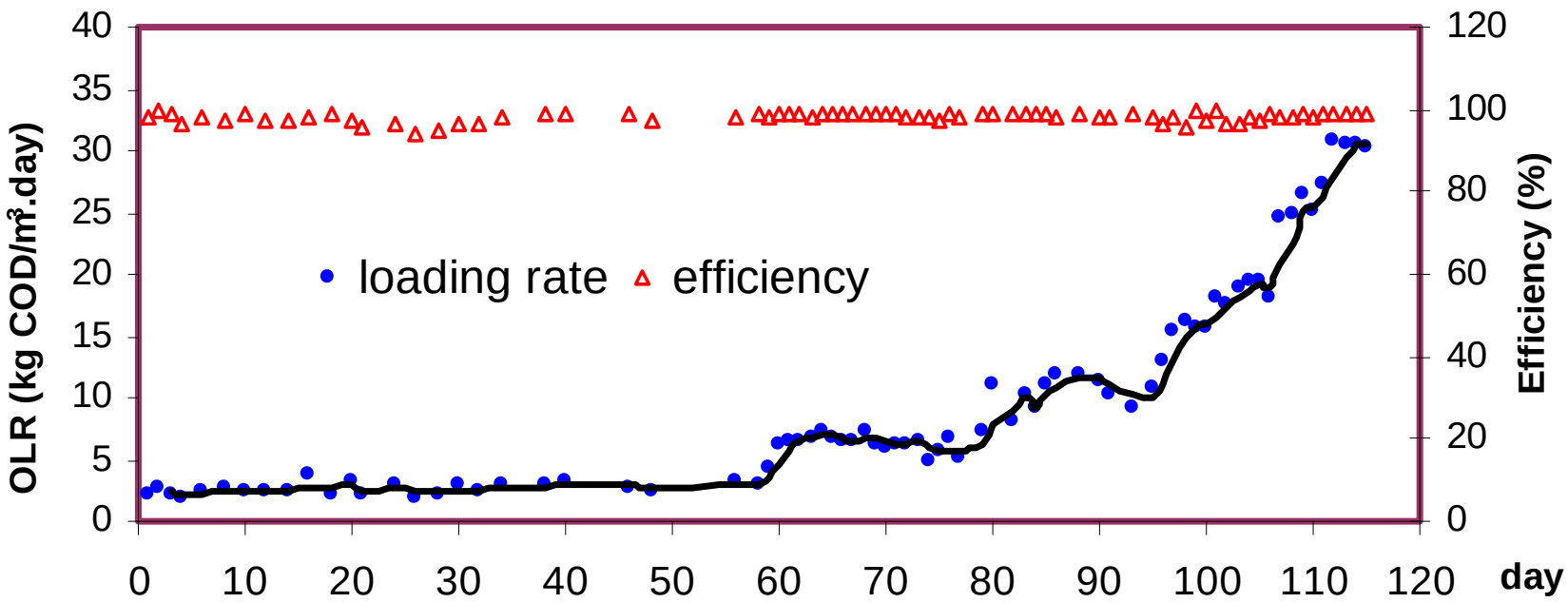


Granule Size Development



- Seed sludge 0.09 mm; shell granule d = 0.5 - 2 mm;
- CR could withstand to Shock Loading.

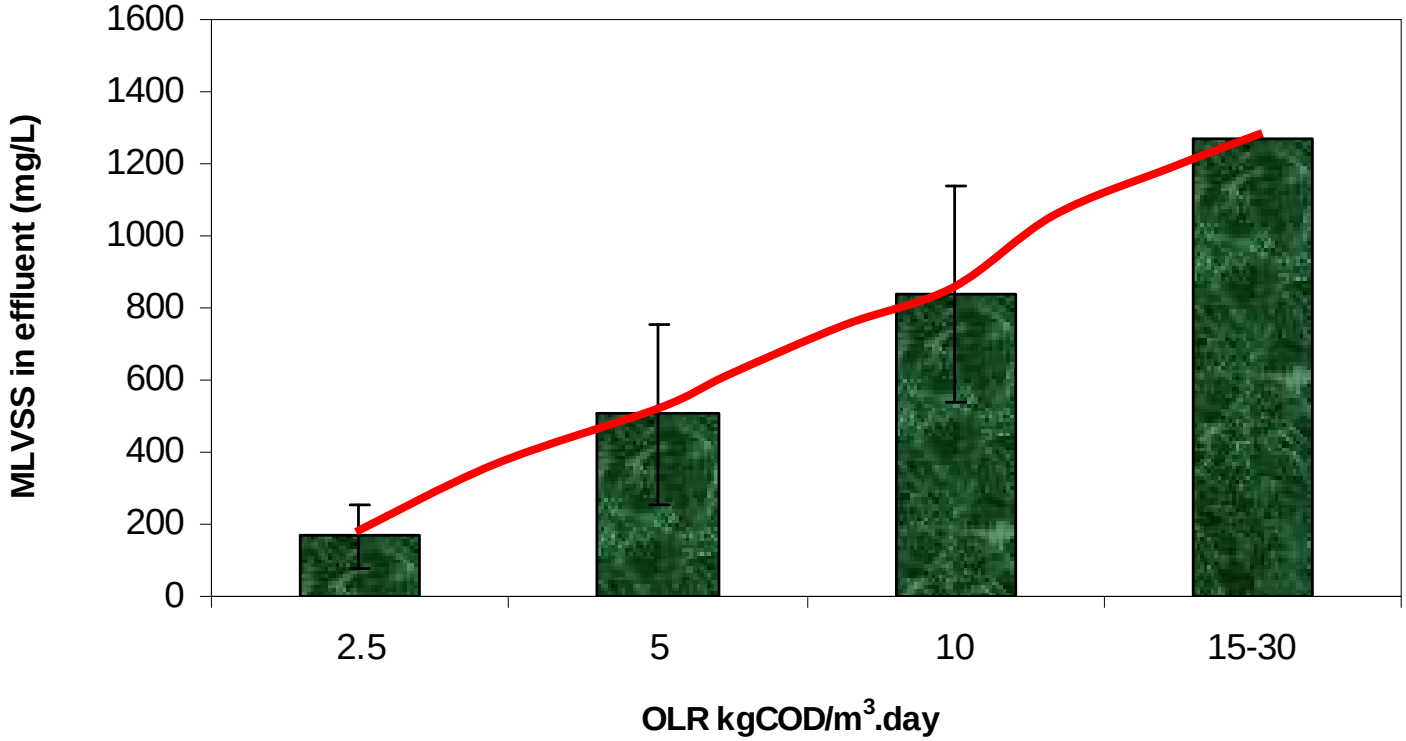
Treatment Efficiency



- OLR can operate from 2.5 – 30 kgCOD/m^3.day;
- COD removal efficiency > 96%;
- SOUR = 46.8 mgO$_2$/L.h [CAS = 18 mgO$_2$/L.h (Liu et al., 2005]

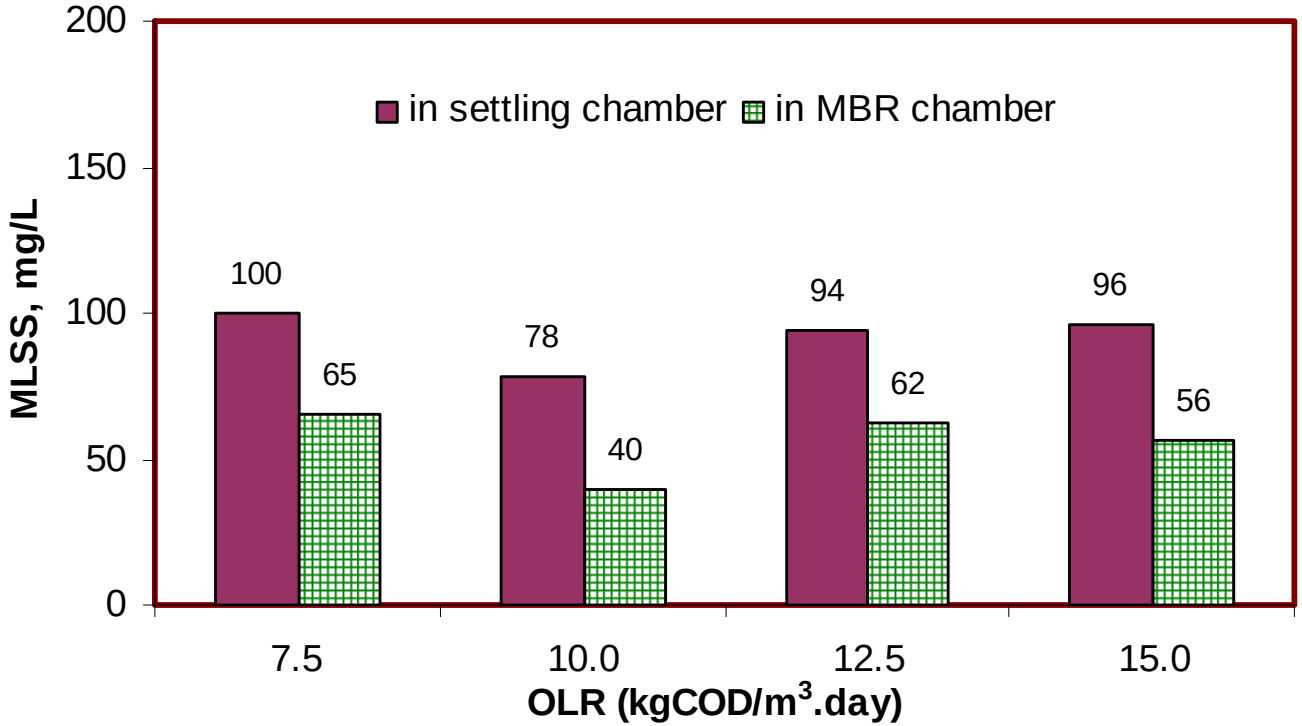
Biomass Conc. in SBAR Supernatant

References	Beun et al., 2002	Arrojo et al., 2004	Cassidy & Belia, 2005
$SS_{effluent}$, mg/L	75-250 (VSS)	150-450 (SS)	42 (SS)
$SS_{influent}$, mg/L	None	200-1200	1742
OLR, kg/m^3.day	2.5 (COD) & 0.2 (N)	7 (COD) & 0.7 (N)	2.6 (COD) & 0.5 (N)
Wastewater type	Synthetic (acetate)	Dairy	Abattoir



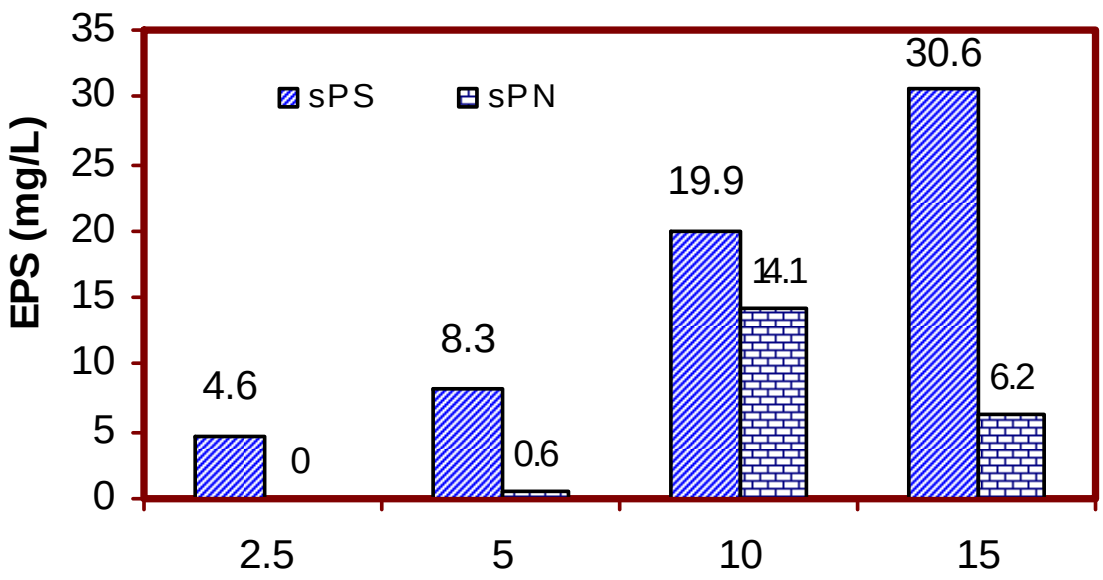
- $MLVSS_{effluent}$ = 200 – 1200 mg/L at varying OLRs ➔ Membrane as an effective post treatment for water reuse and recycling;

MLSS in System



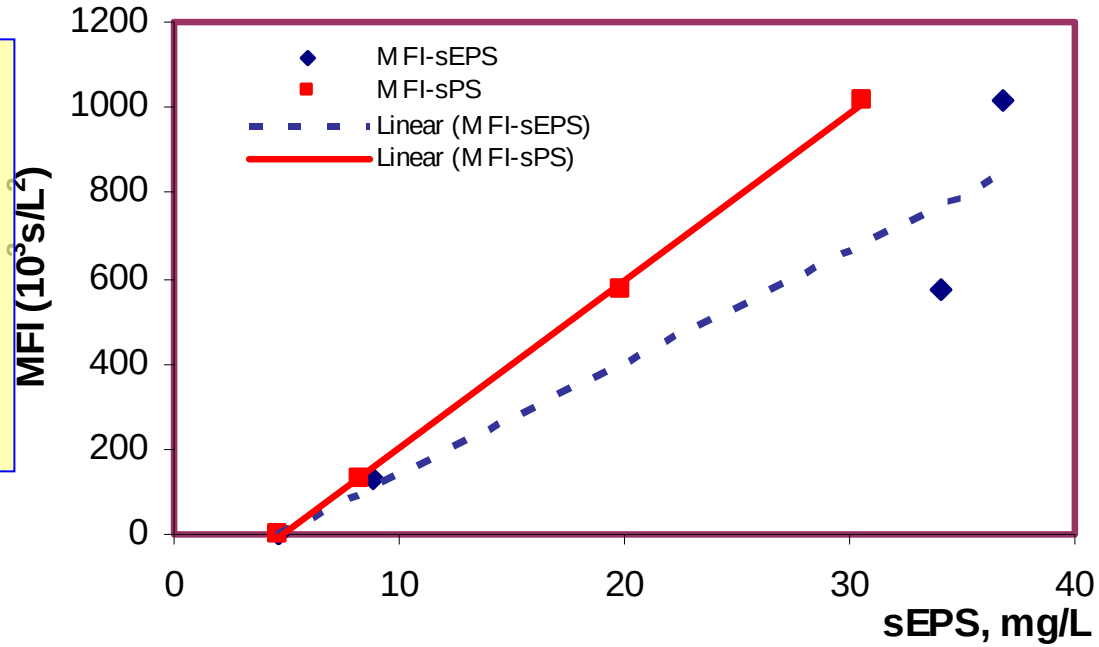
- **The amount of biomass reduction due to aeration in membrane chamber was 34.0-48.7% at various OLRs;**
- **MFI of mixed liquor in the MBR chamber was 29% higher than that of the supernatant from SBAR➔ fouling not caused by MLSS**

Soluble EPS

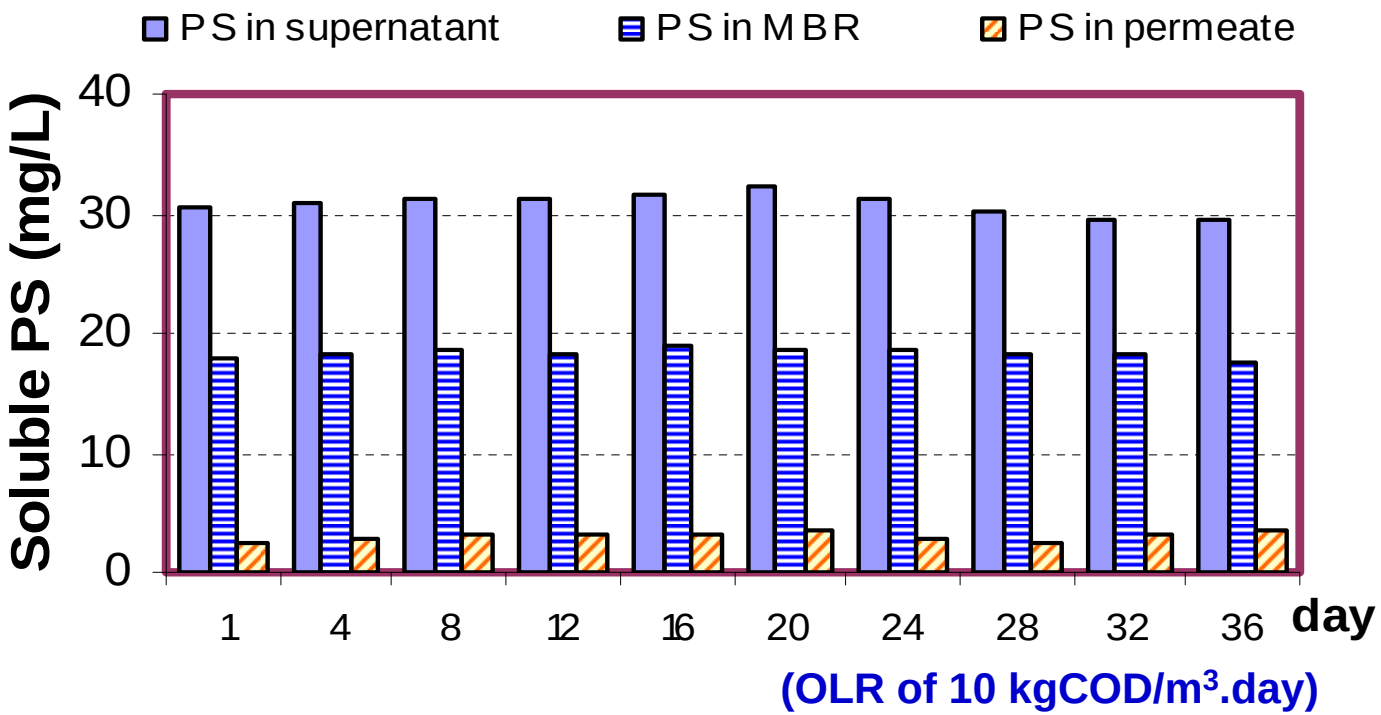


- Soluble PS increased with OLRs (84 ± 18% sEPS);
- PS causes membrane fouling in granulation's supernatant;
- Fouling effect is similar to that of submerged MBR's supernatant.

- Granule MBR has high sPS/sEPS ratio as compared with MBRs [sPS = 58%sEPS (*Liang et al., 2007*]

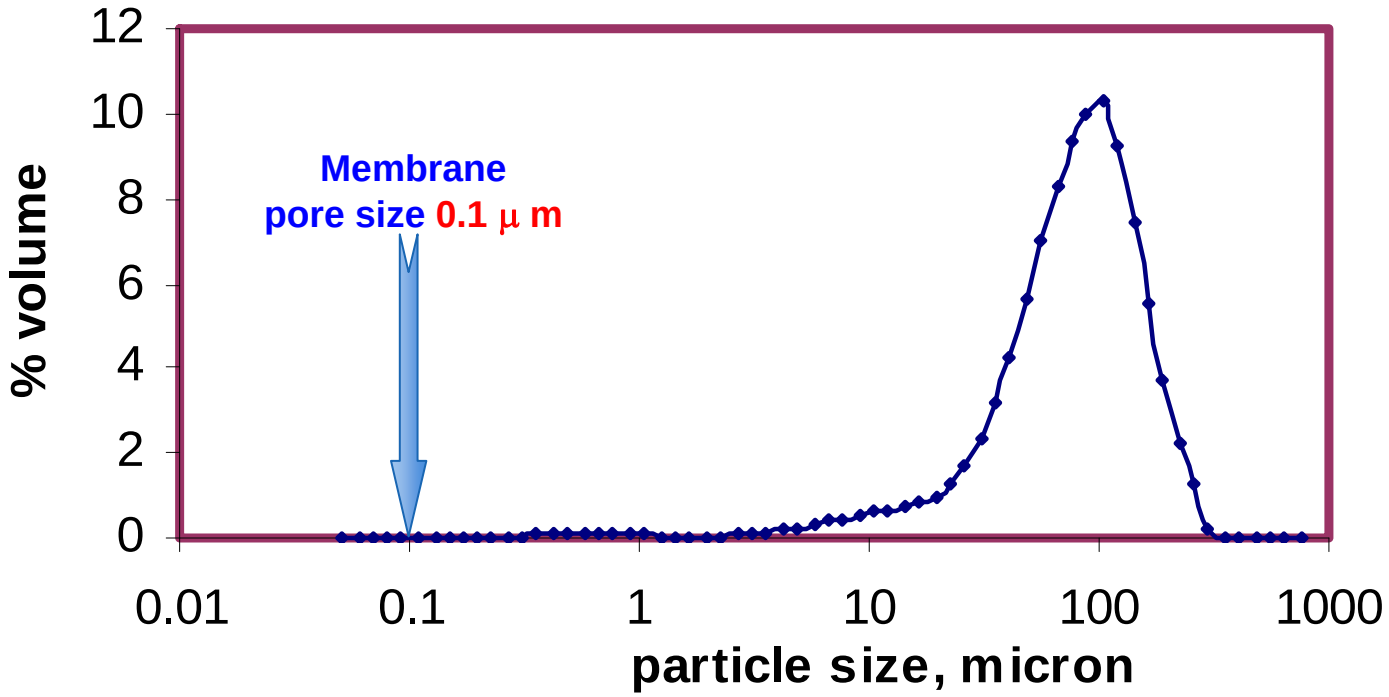


Soluble PS



- **Soluble PS was 30.8±0.8, 18.3 ± 0.3 and 3.0 ± 0.2 for SBAR supernatant, bulk liquid in MBR and permeate ➔ soluble PS degradation in MBR chamber, deposit on membrane and passing through permeate was 40.6, 49.7 and 9.7% respectively.**

Particle Size Distribution



- Mean size of particles in MBR chamber was 95.8 μ m, always greater than 0.3 μm (membrane pore size of 0.1 μ m).

Membrane Resistance

Resistance	Resistance (m^{-1})	Percentage (%)
Total resistance (R_T)	$3.156*10^{12}$	
Intrinsic resistance (R_m)	$0.123*10^{12}$	4
"Cake layer" resistance (R_c)	$1.179*10^{12}$	37
Irreversible resistance (R_f)	$1.852*10^{12}$	59

- No cake layer, only "thin biofilm layer" on membrane surface
- Irreversible fouling mainly contributes to fouling of membrane (59%) [in other MBR mainly caused by cake resistance];
- Fouling of granulation's supernatant is due to PS deposition on membrane which caused irreversible fouling.

Granule-MBR vs Conventional MBR

Items	Granule-MBR	MBRs
Operating mode	Batch	Continuous
Oxygen transfer limitation	No	Yes
MLSS, mg/L	40-65	8,000-12,000
Resistance	Irreversible (only thin biofilm)	Cake (thick cake layer)
Fouling reason	PS	SS (Cake), EPS
Fouling potential	Less (in research)	High
sPS/sEPS, %	84	58
Particle size, μm	95.8	-
Loading (kg COD/m^3.day)	10-15	<8
Simultaneous Nitrification/Denitrification	Yes	No

Conclusions

- Shell carrier could be support media for aerobic granule cultivation;

- Shell granule coupled MBR could operate at high OLR (15 kgCOD/m^3.d);

- Soluble PS in supernatant comprising of 84±18% of soluble EPS which is higher than other MBRs. It increases with OLRs & the key fouling factor in aerobic granulation coupled baffled MBR;

- Fouling potential increases linearly with soluble PS in supernatant from granulation process ➔ deposition of PS on membrane surface/pores ➔ Irreversible fouling.

Thank you for your attention!