Influence of Hydrodynamic and Physico-Chemical Approaches on Fouling Mitigation in a Membrane Bioreactor

Examination Committee:

Prof. C. Visvanathan (chairman)
Dr. Preeda Parkpian
Dr. Oleg V. Shipin
Dr. Mukand S. Babel

S. Jamal Khan

Presentation Outline

- External examiner comments
- Research Background
- Research Objectives
- Methodology
  - Phase I
  - Phase II
- Results and discussion
  - Phase I
  - Phase II
- Conclusion and Recommendations
- Contribution to Membrane Technology

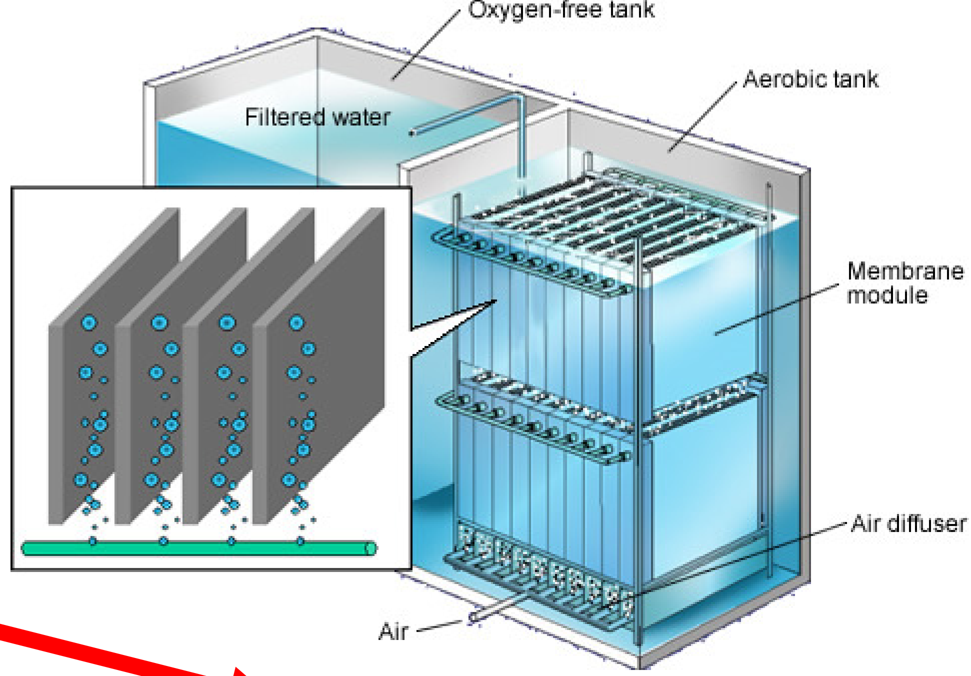
External Examiner Comments

- The results and discussion on variation in particle size with mixing intensity is excellent. At which stage of the MBRs operation in Phase I, PSD was determined? Provide additional figure with cumulative volume (%) versus particle size (µm).
  - PSD was determined at the end of the Phase I (120 days operation) and addition figure as suggested by the examiner was provided in Appendix C (page 113)
- Provide additional curves among parameters shear intensity (G), particle size, SCOD, EPS and SOUR.
  - Additional curves and discussion were provided in additional appendix (Appendix-F; page 127)
- In pages 67 and 68, please explain the trend of variation of SCOD in terms of polymer and PAC concentration respectively?
  - Additional paragraphs were added to explain the trend of variation of SCOD in terms of polymer and PAC concentration, respectively.
- The empirical relationship obtained between the fouling rate and specific cake resistance at different mixing rates is excellent.

Research Background

Membrane bioreactor (MBR)

Combination of biological process by activated sludge + direct solid liquid separation by membrane filtration



Advantages

1. High effluent quality
2. Good disinfection capability
3. High volumetric loading
4. Less sludge production
5. Small footprint & compactness

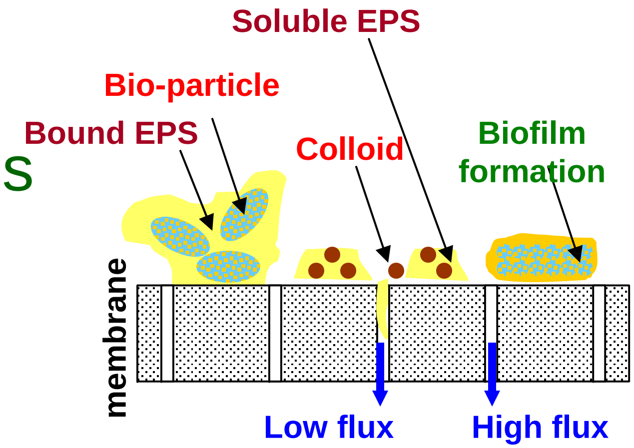
Research Background

Membrane fouling

Accumulation of substances on membrane surface and/or within membrane pores resulting in deterioration of membrane performance

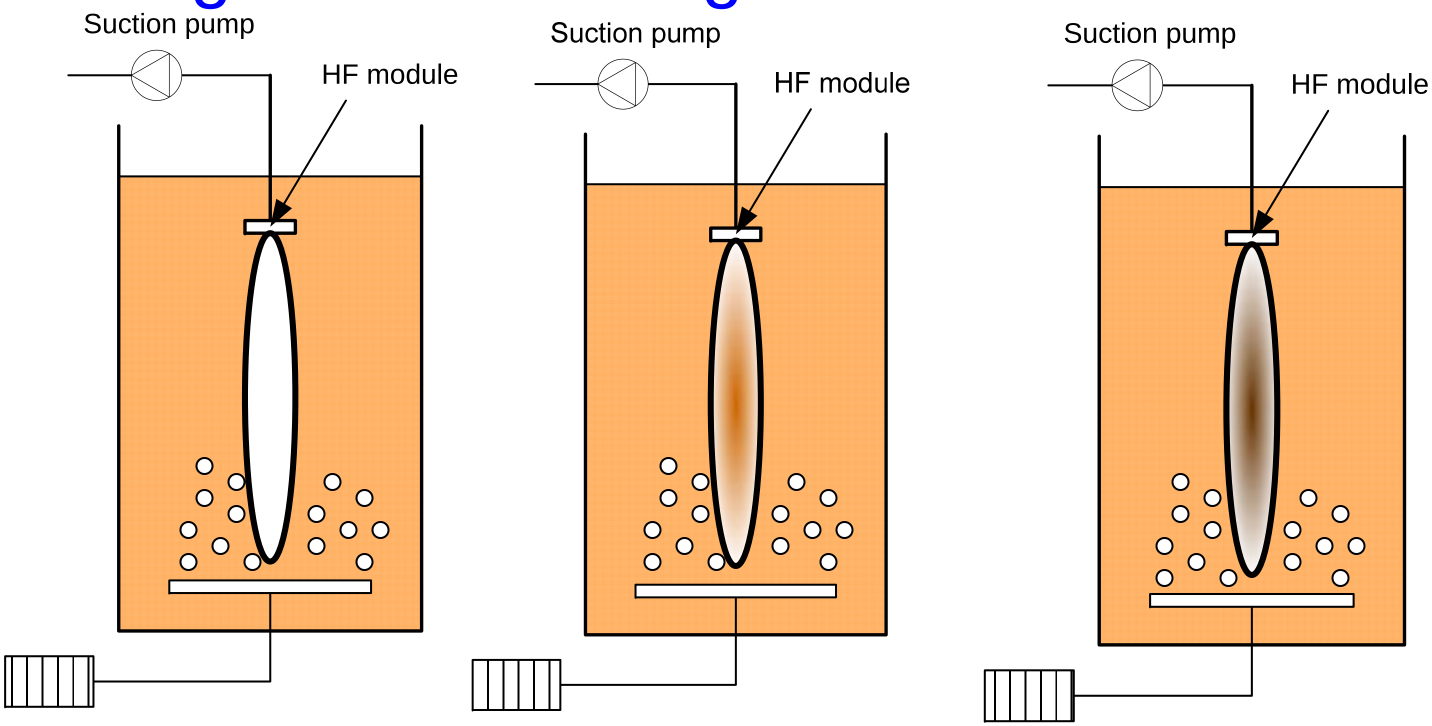
Major foulants

1. Suspended & colloidal particles
2. Bound and Soluble EPS
3. Biological growth



Research Background

Fouling in HF submerged MBR



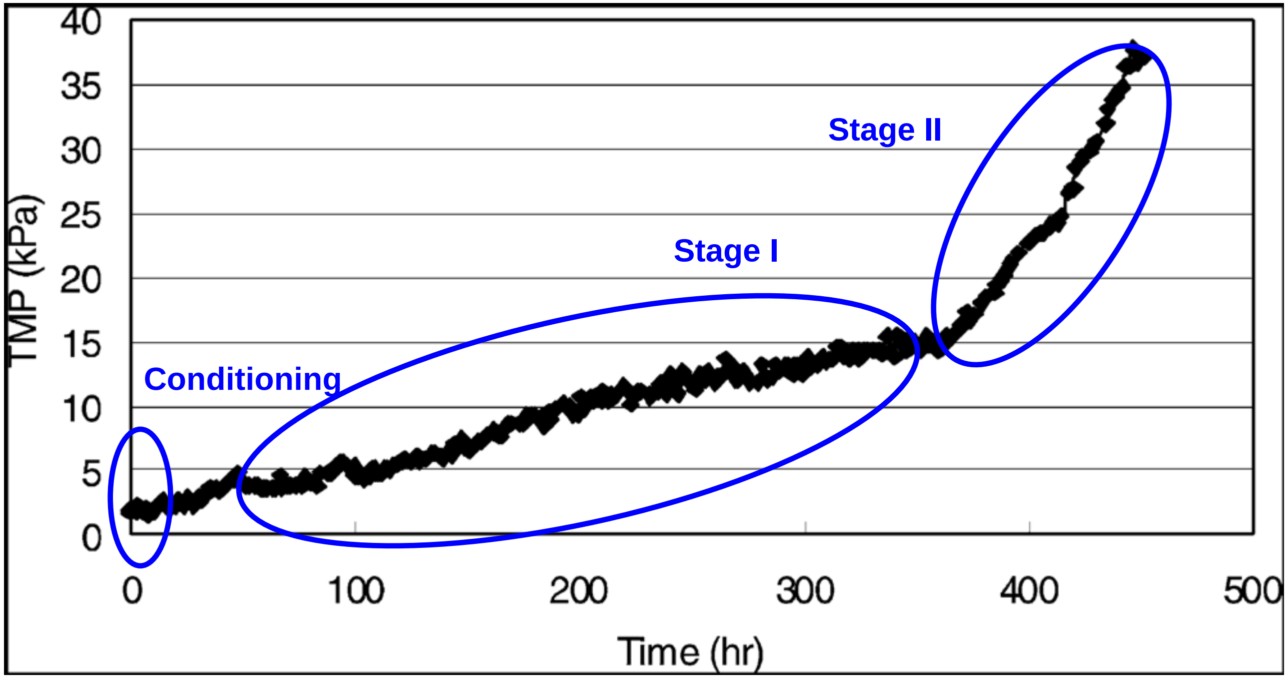
Start-up:
(Membrane conditioning)
Effective filtration area ≈ 100%
Local flux << Critical flux

Stage I:
(Linear gradual TMP rise)
Effective filtration area decrease
Local flux ≈ Critical flux

Stage II:
(Rapid TMP rise: TMP jump)
Effective filtration area becomes critical
Local flux > Critical flux

Research Background

Membrane fouling tendency



B.D. Cho and A.G. Fane, Fouling transients in nominally sub-critical flux peration of a membrane bioreactor, J. Membr. Sci. 209 (2002) 391-403

- Effective fouling control strategy:
  1. Retard Stage I fouling
  2. Avoid Stage II fouling

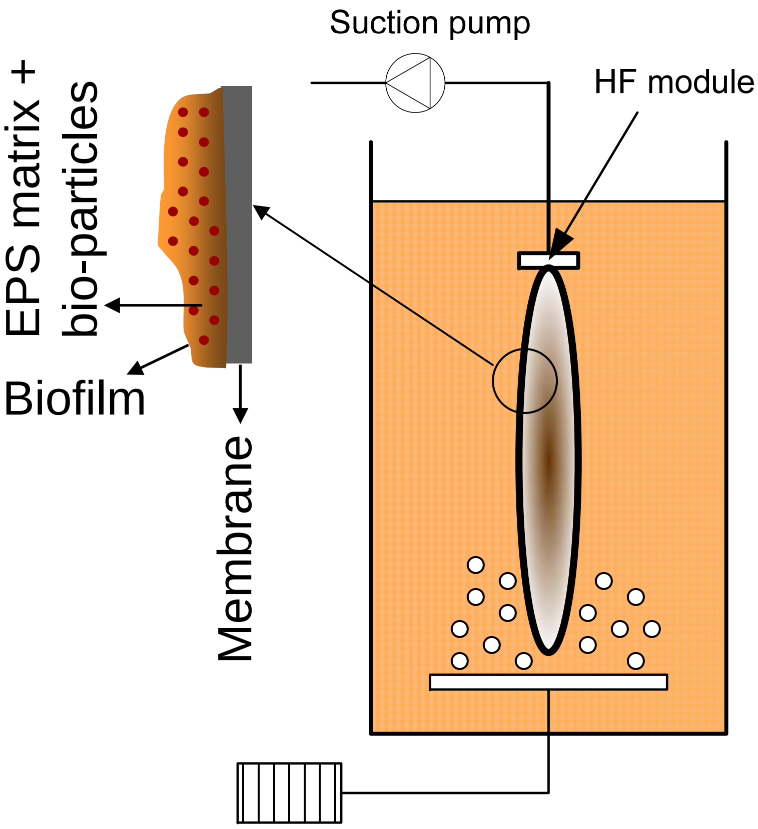
Research Background

- High aeration intensity is practiced to hydrodynamically mitigate fouling in submerged MBR operation
- However, high aeration rates influence the biological conditions including
  - Growth rate
  - F/M ratio
  - Microbial community
- Biofloc deposit in low shear stress regions (vicinity of surrounded fibers) leading to local cake layer formation

Ineffective membrane scouring with operational duration instigates the need to explore alternative hydrodynamic techniques

Research Background

- Influence of sludge characteristics on fouling behavior is unclear
- Limited research on biofilm structure variability with MBR operation
- Biofilm permeability key to fouling control mechanisms
- Factors affecting biofilm permeability require further investigation



Research Background

Fouling mitigation approaches

Physico-chemical Approach

- ✓ Coagulants
- ✓ Adsorbents

Microbiological Approach

- ✓ SRT
- ✓ F/M ratio

Hydrodynamic Approach

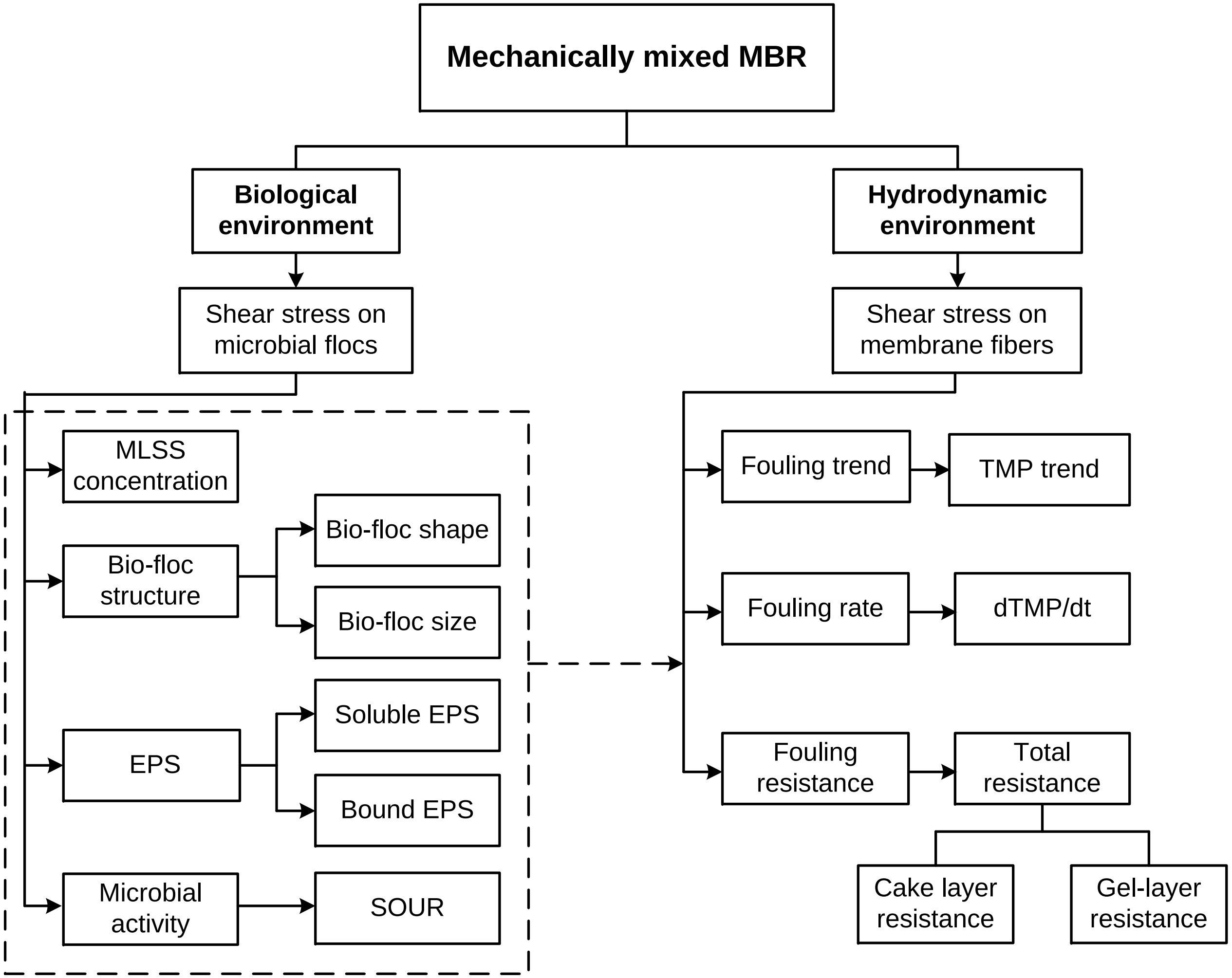
- ✓ Cross-flow velocity
- ✓ Aeration intensity

Research Objectives

- To investigate the influence of mechanical mixing rates in submerged hollow fiber MBRs on membrane filtration performance and sludge characteristics;
- To determine optimum mechanical mixing condition based on filtration performance and sludge filterability characteristics;
- To develop hybrid MBRs by the addition of kaolin clay, powdered activated carbon (PAC) and Nalco® cationic polymer (MPE50) to MBR systems.
- To investigate the fouling propensity among the hybrid MBRs and compare with conventional MBR;
- To analyze modified sludge characteristics in hybrid MBRs and determine the most suitable hybrid MBR system that achieve low fouling rates

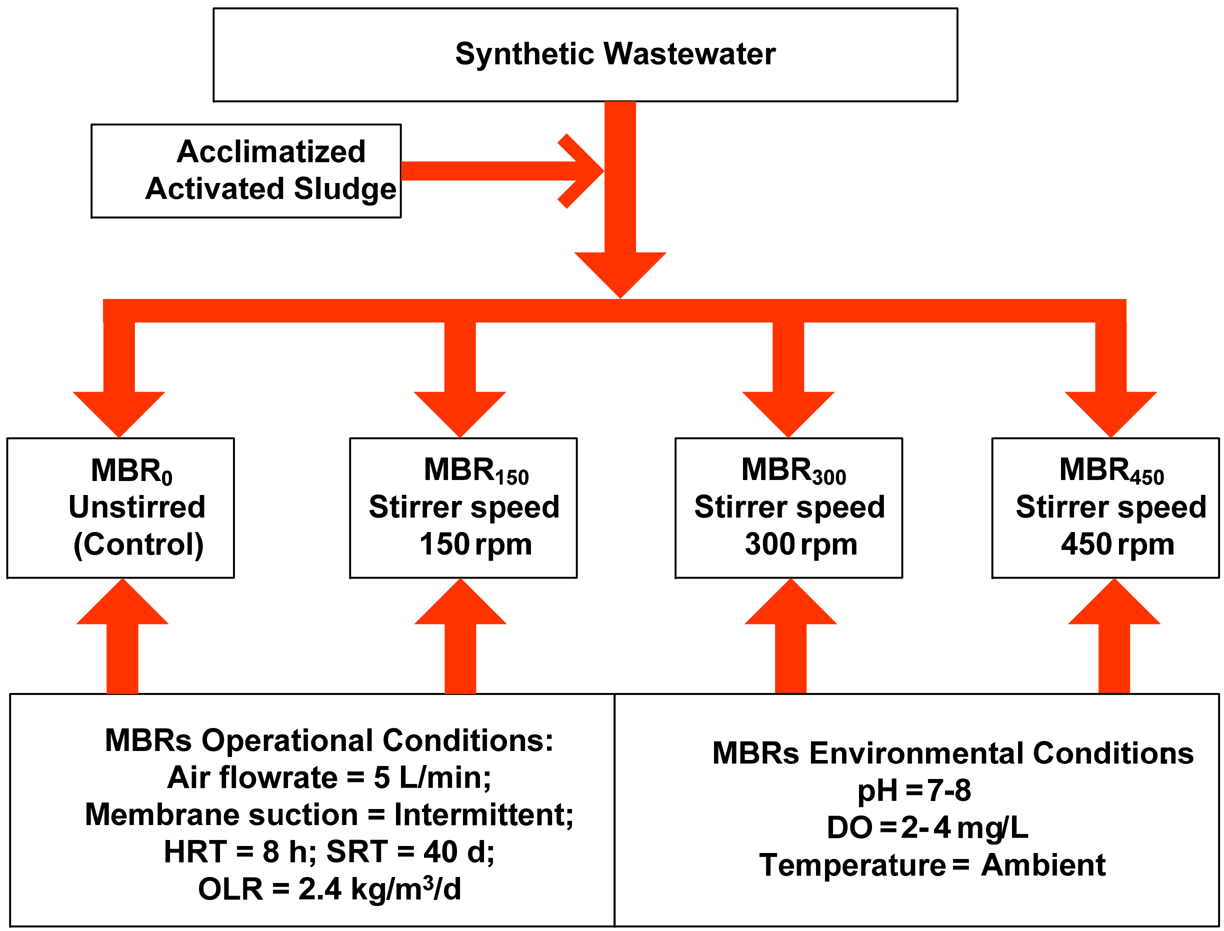
Methodology

Roadmap of Phase I study



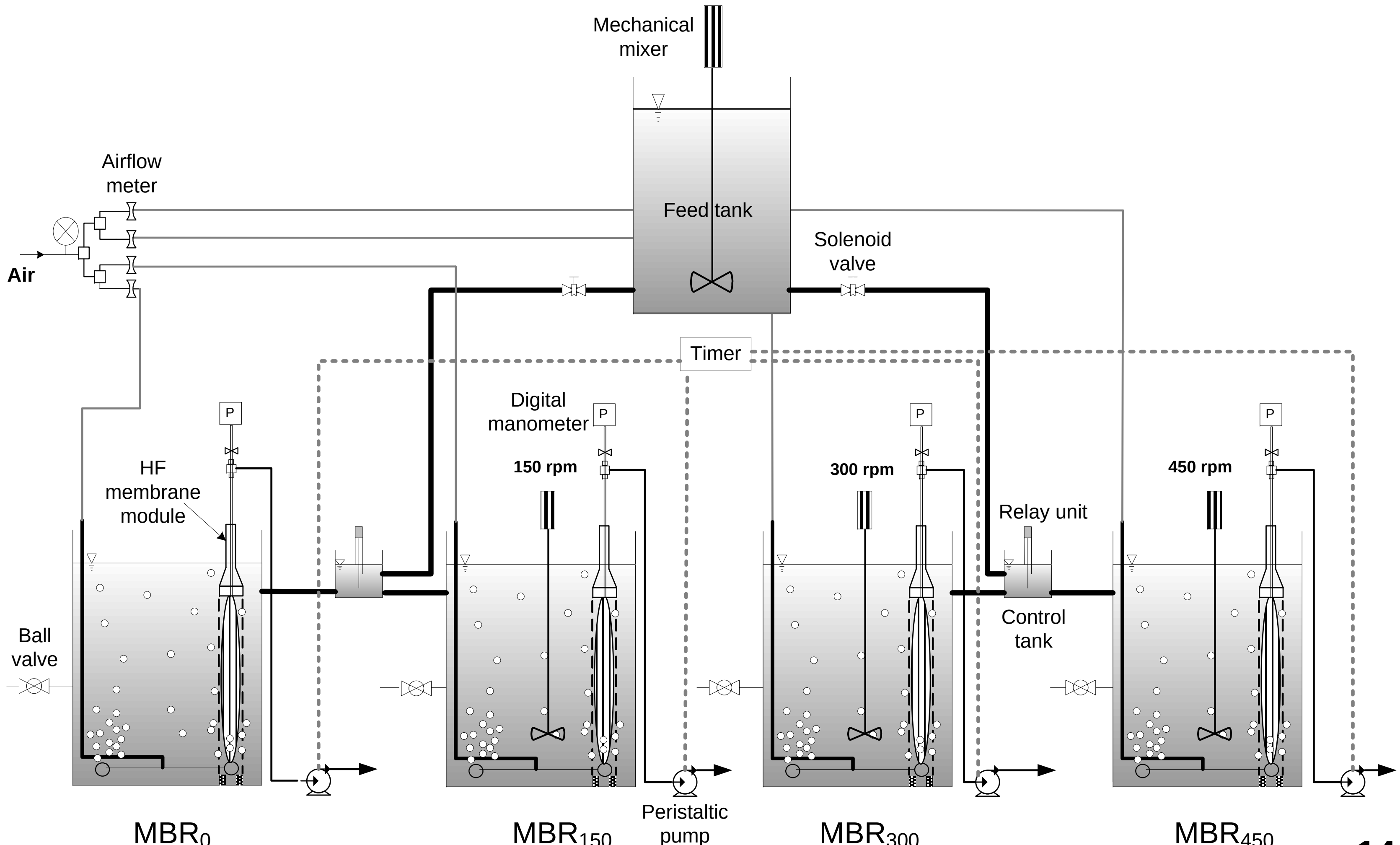
Methodology

Phase I: Operational conditions



Methodology

Laboratory-scale submerged-MBRs



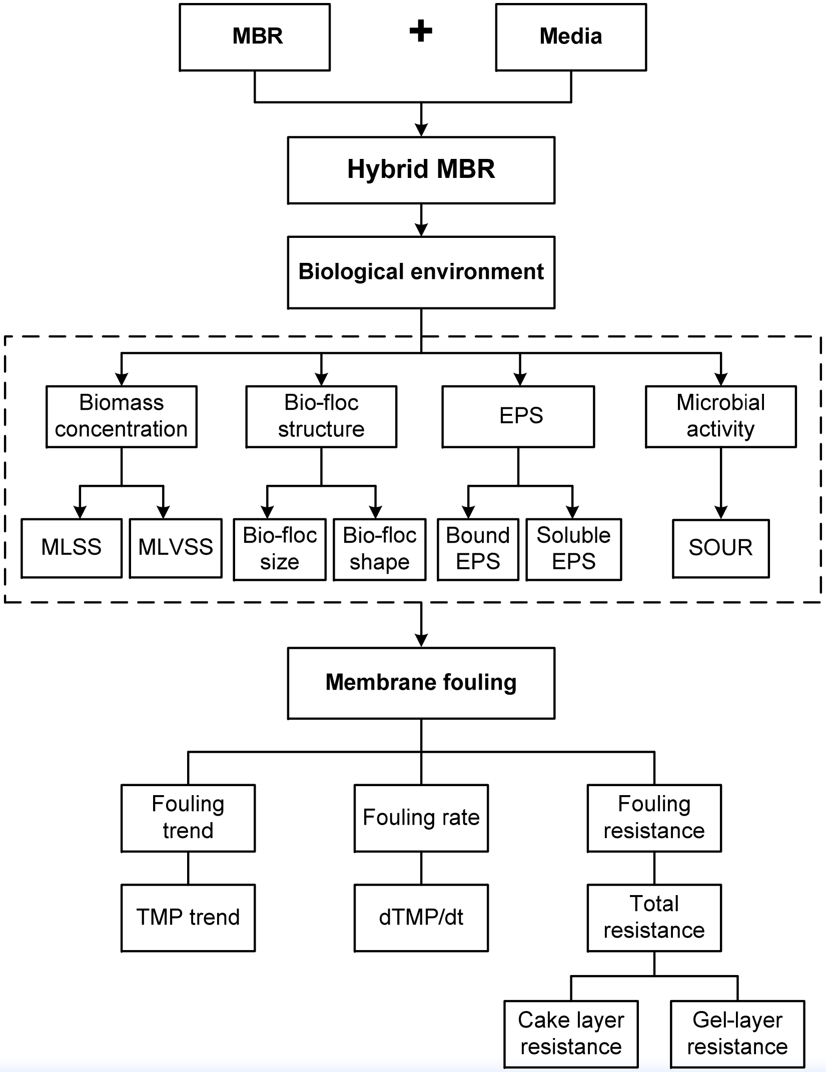
Methodology

Shear intensity (G) in MBRs

MBR	Mechanical mixing (rev/s)	Pneumatic mixing (m^3/h)	Reynolds Number (N_R)	Total power (W)	Shear intensity (G) (1/s)
MBR_0	0	0.3	0	0.17	83
MBR_{150}	2.5	0.3	10,000	0.34	117
MBR_{300}	5.0	0.3	20,000	1.55	249
MBR_{450}	7.5	0.3	30,000	4.81	439

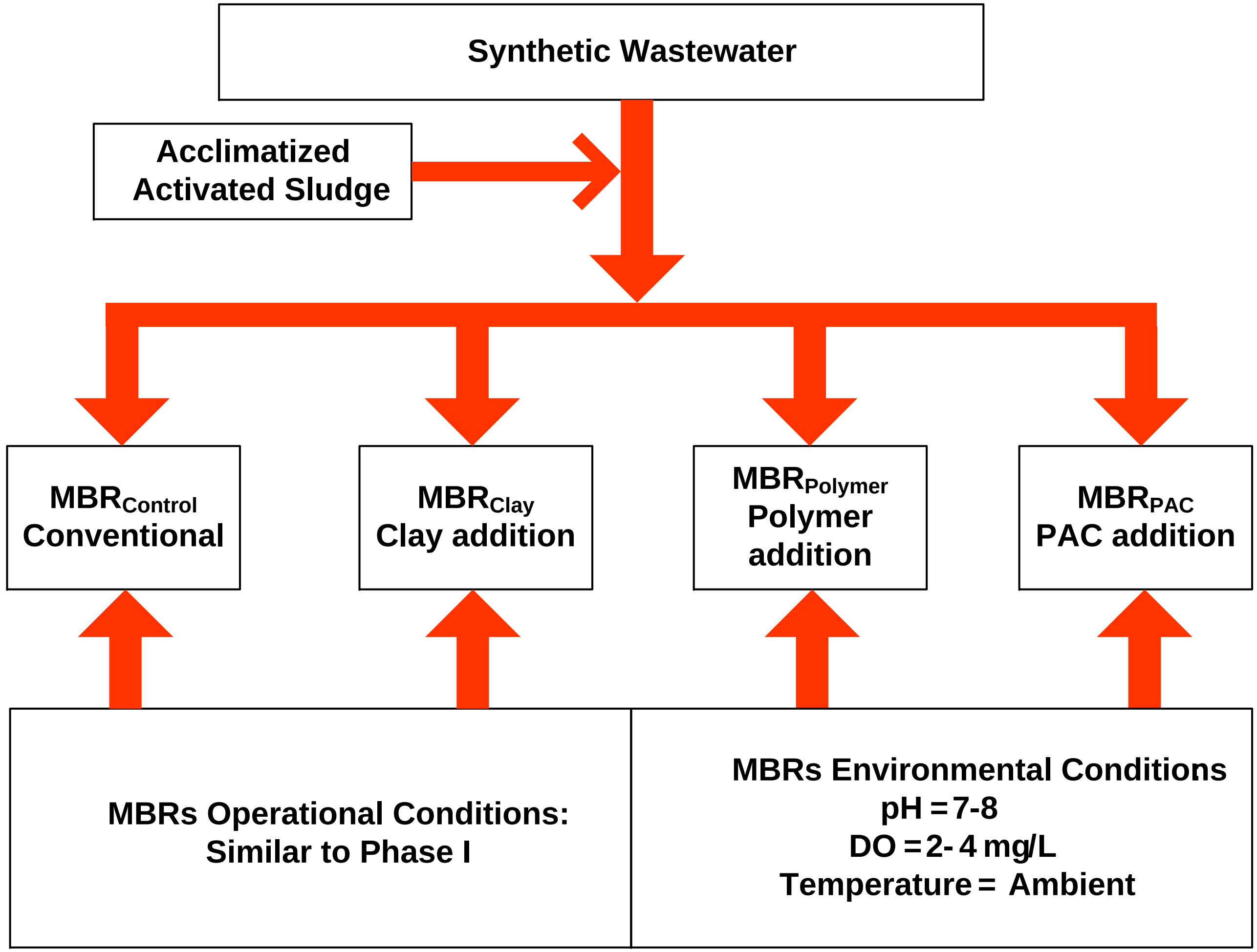
Methodology

Roadmap of Phase II Study



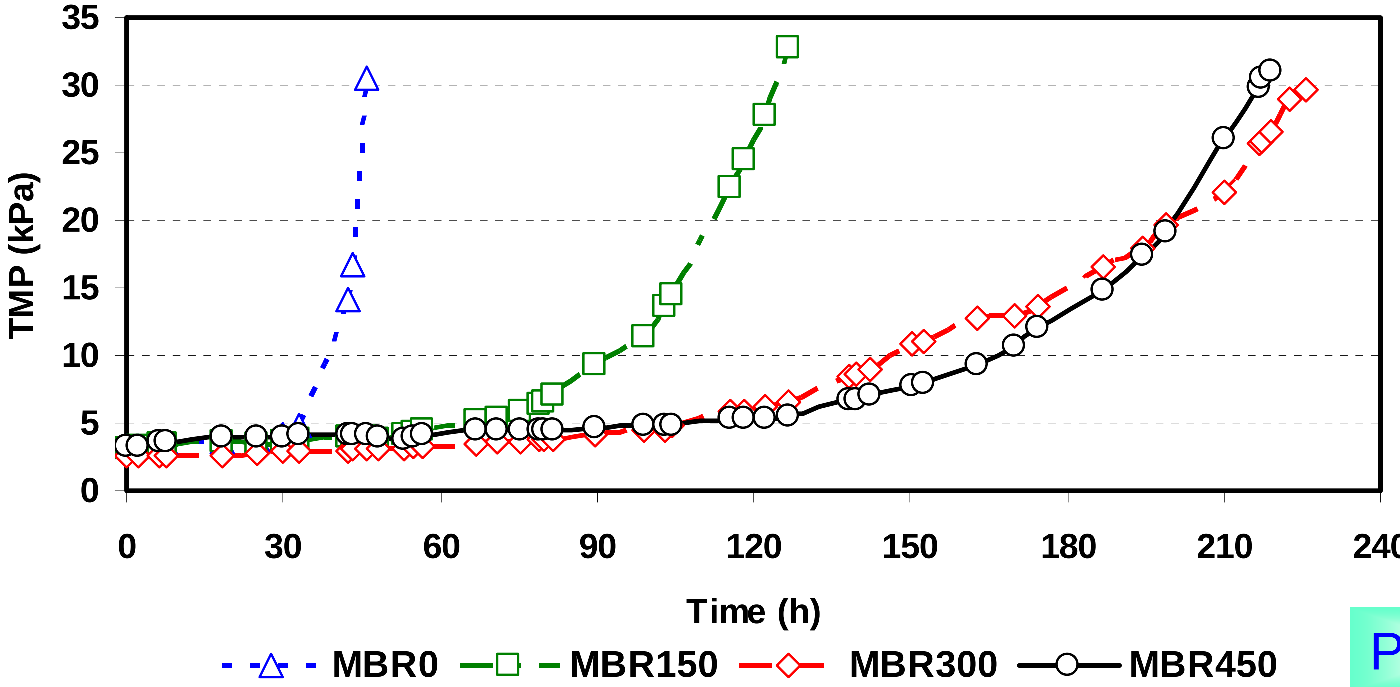
Methodology

Phase II: Operational conditions



Results and Discussion: Phase I

Filtration behaviors in MBRs

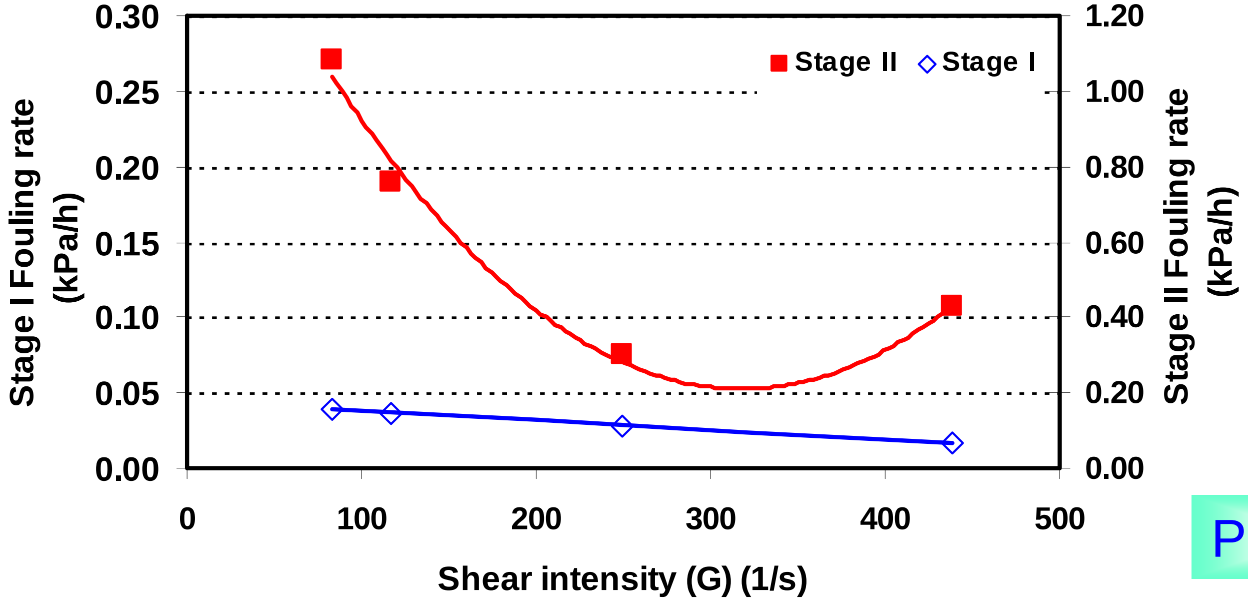


Page 52

- MBR$_0$ fouled rapidly followed by MBR$_{150}$ and lastly by MBR$_{300}$ and MBR$_{450}$;
- Filtration duration could not be further improved in MBR$_{450}$ with higher G;
- TMP profiles exhibited two-stage fouling process.

Results and Discussion: Phase I

Membrane fouling rates

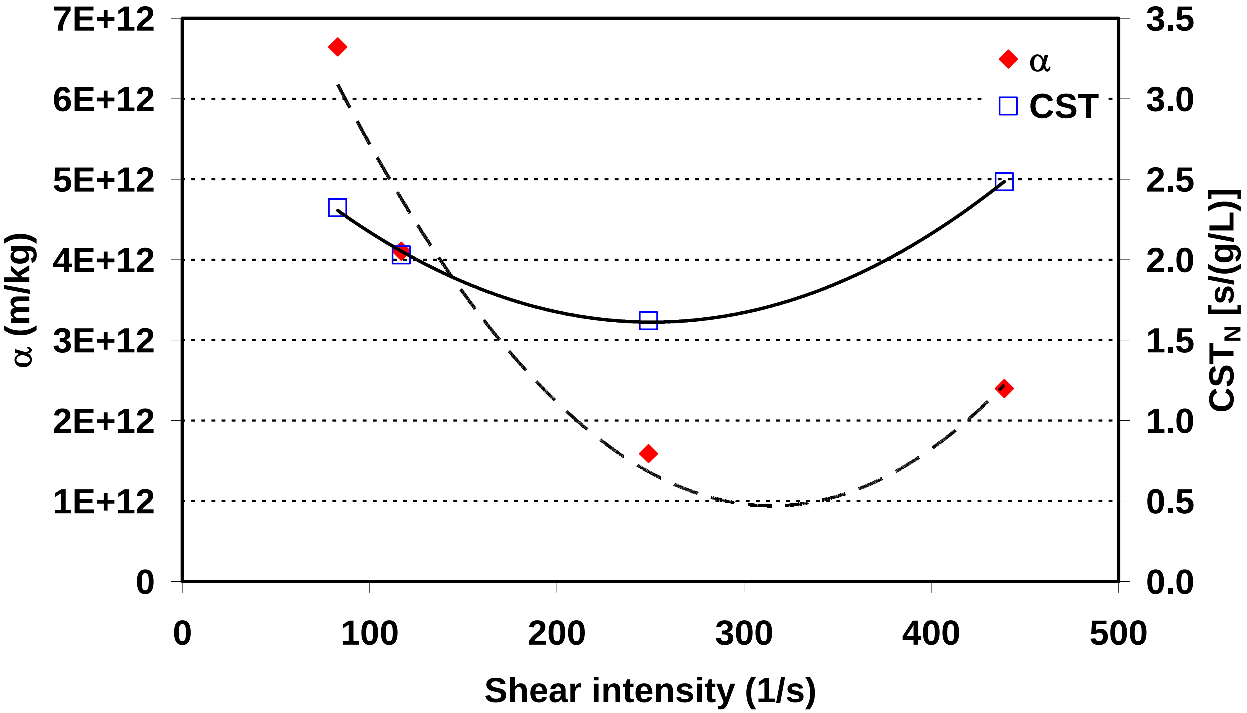


Page 54

- First stage fouling rate relatively decreased with increase in shear intensity (G) due to retarded biofloc deposition;
- Second stage fouling rate initiated after cake formation and fouling rate significantly decreased with increase in G up to 249 s^{-1} beyond which it deteriorated;
- G of certain level is feasible beyond which it becomes disadvantageous.

Results and Discussion: Phase I

Sludge filterability characteristics

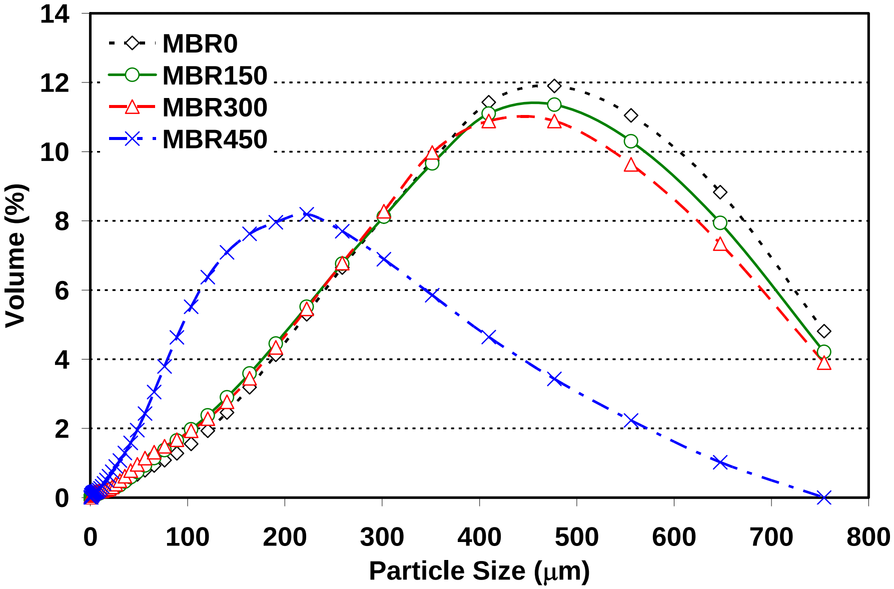


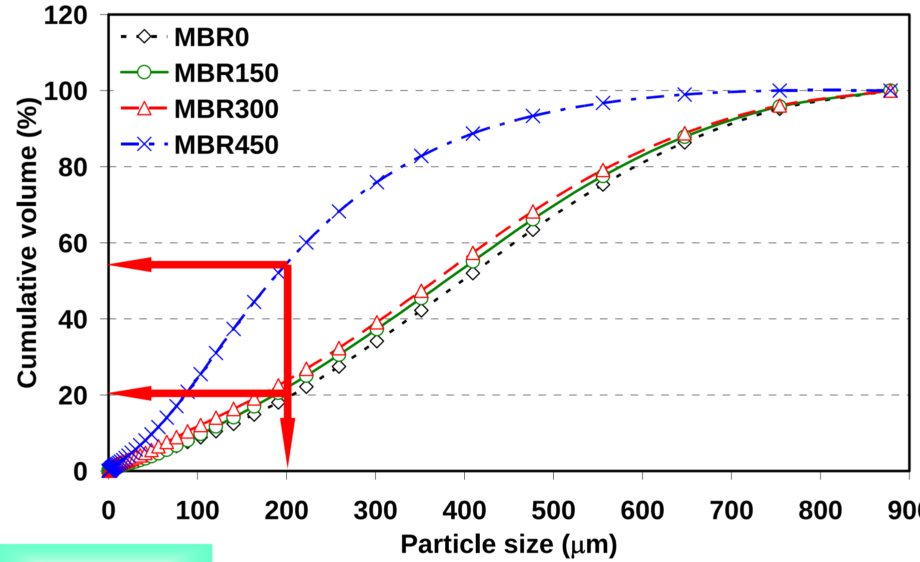
Page 55

- Sludge filterability characterized by CST_N and specific cake resistance (α);
- Filterability improved with increase in shear intensity (G) up to 249 s^{-1};
- Mixing condition in MBR_{300} was optimum based on prolong filtration and improved sludge filterability characteristics.

Results and Discussion: Phase I

Particle size distributions (PSD) in MBRs





Page 56

- Bio-particle size relatively reduced with increase in shear intensity up to 249 s^{-1};
- Extreme turbulent condition (MBR_{450}) exhibited small particles and scattered distribution;
- Bio-flocs could withstand shear stress up to certain level beyond which they ruptured.

MBR	Particle size (µm)
MBR_0	398
MBR_{150}	379
MBR_{300}	367
MBR_{450}	183

S. Jamal Khan

Results and Discussion: Phase I

Resistance-in-series model

$$J = \frac{\Delta P}{\mu R_t f_t}, \quad f_t = e^{-0.0239(T-20)} \qquad \text{Eq. 1}$$

$$R_t = R_m + R_c + R_f \qquad \text{Eq. 2}$$

Membrane fouling resistances

Page 54

Resistances	MBR_0	MBR_{150}	MBR_{300}	MBR_{450}
R_t ($\times 10^{12}$ m^{-1})	79.46	83.51	76.55	76.57
R_c ($\times 10^{12}$ m^{-1})	78.36	82.31	75.10	75.43
R_f ($\times 10^{12}$ m^{-1})	0.72	0.77	0.85	0.75
R_m ($\times 10^{12}$ m^{-1})	0.39	0.43	0.60	0.39
R_c/R_t (%)	**98.6**	**98.5**	**98.1**	**98.6**

Results and Discussion: Phase I

Empirical model based on cake filtration theory

According to cake filtration theory

$$R_c = \frac{\alpha . V . C_b}{A_m} \qquad \text{Eq. 3}$$

Based on membrane resistance analysis

$$R_t \approx R_c \qquad \text{Eq. 4}$$

$$\Rightarrow \frac{dR_t}{dt} = \left(\frac{\alpha . C_b}{A_m} \right) \frac{dV}{dt} \qquad \text{Eq. 5}$$

where C_b is assumed as constant (6-8 g/L)

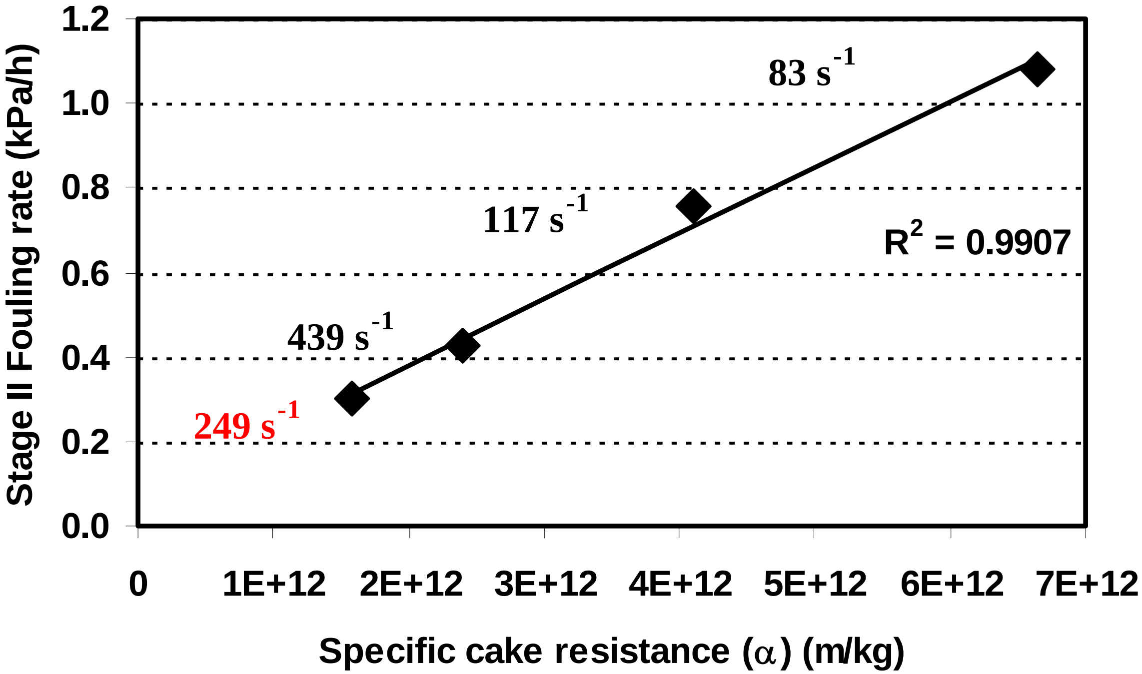
Page 64

Results and Discussion: Phase I

Empirical model based on cake filtration theory

$$\Rightarrow R_t \propto \alpha \qquad \text{Eq. 6}$$

- Strong linear relationship b/w Stage II fouling rate and specific cake resistance (*α*);
- Stage II fouling rate and '*α*' decreased up to G value of 249 s^{-1} beyond which these parameters deteriorated;
- '*α*' can be reliable parameter to predict extent of fouling rate.

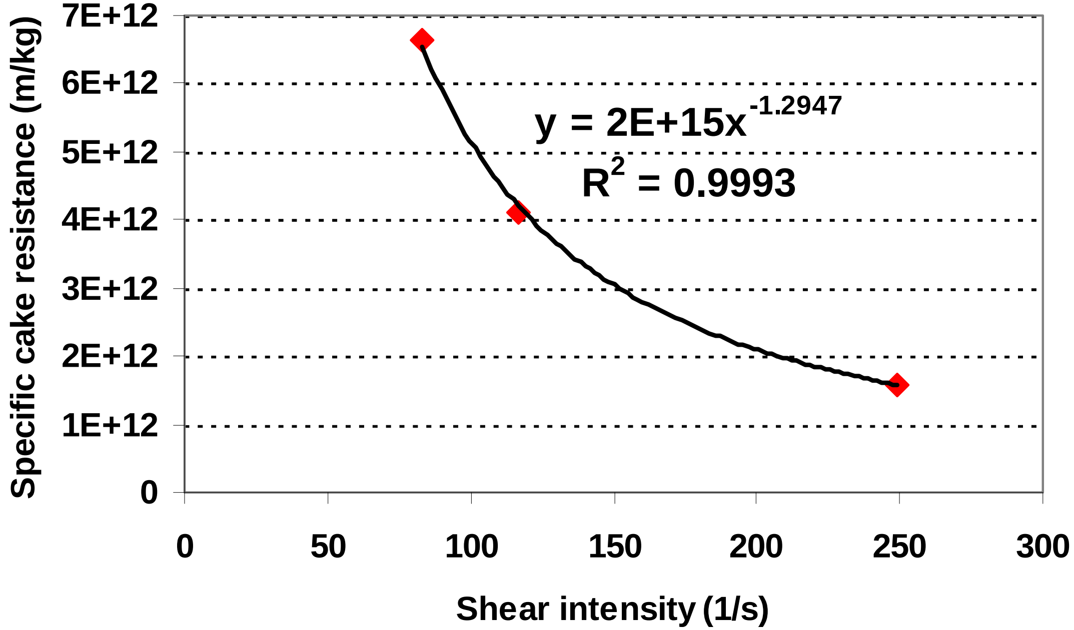


Page 63

Results and Discussion: Phase I

Empirical model based on cake filtration theory

Relationship established b/w shear intensity (G) (83-249 s^{-1}) and 'α'



Page 65

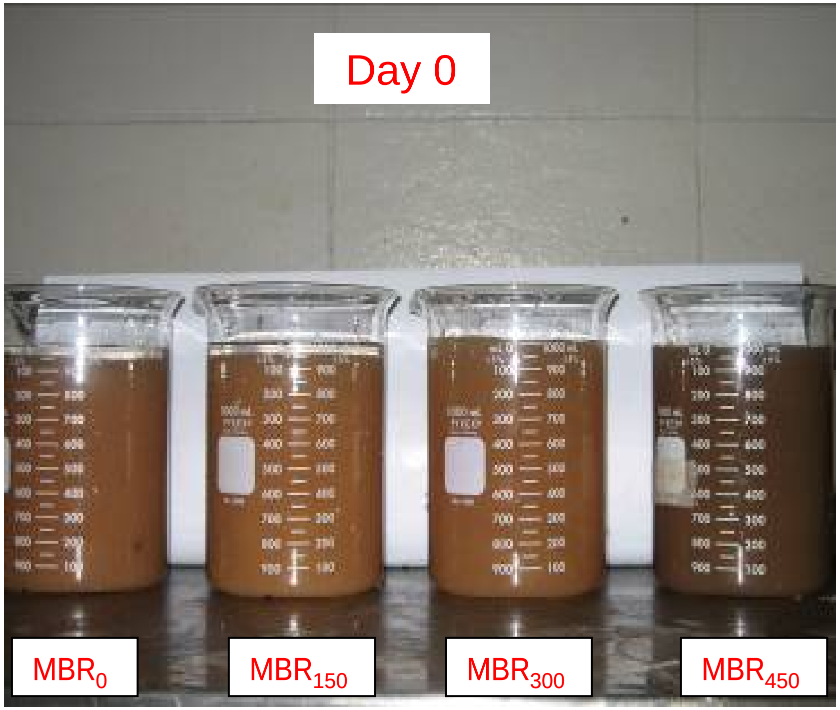
According to Darcy's Law at constant flux

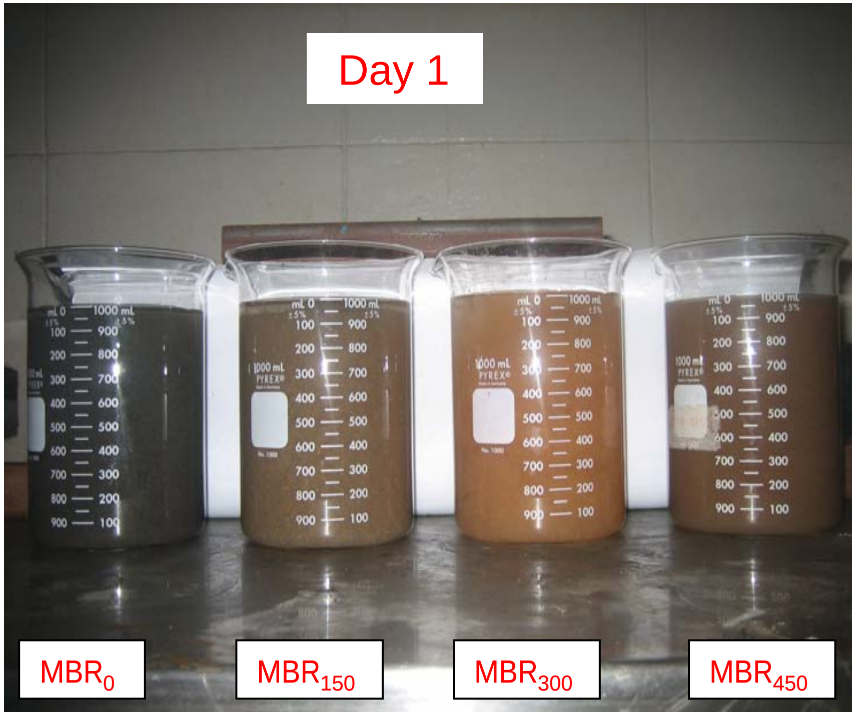
$$\therefore \frac{dR_t}{dt} = \left(\frac{1}{\mu.J}\right)\frac{dTMP_t}{dt} = \frac{\left[2\times10^{+15}\cdot G^{-1.3}\right]\cdot C_b}{A_m}\left(\frac{dV}{dt}\right)$$

Eq. 7

Results and Discussion: Phase I

Simulation of biopolymers in biofilm (5-day period)



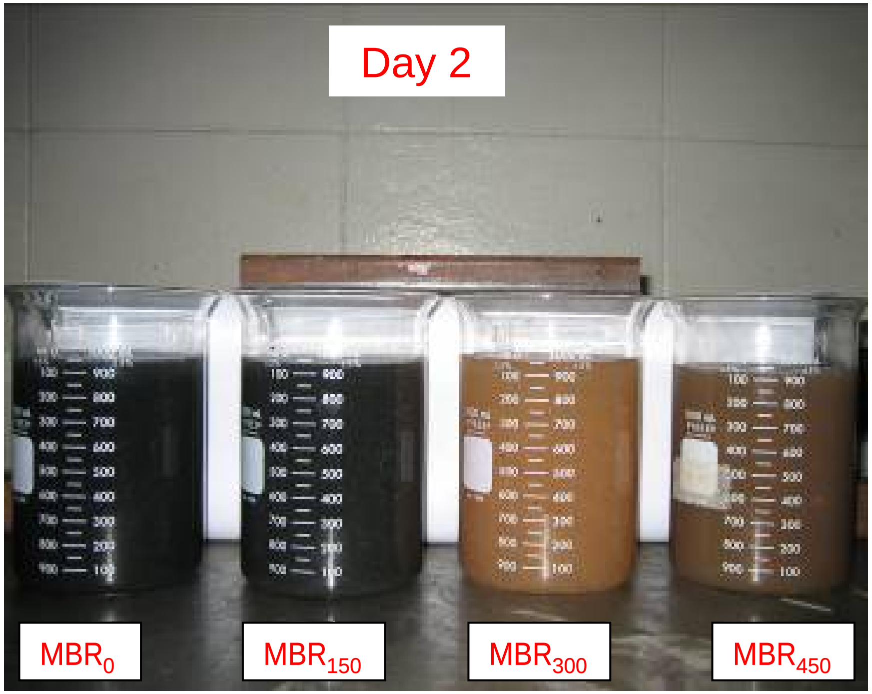


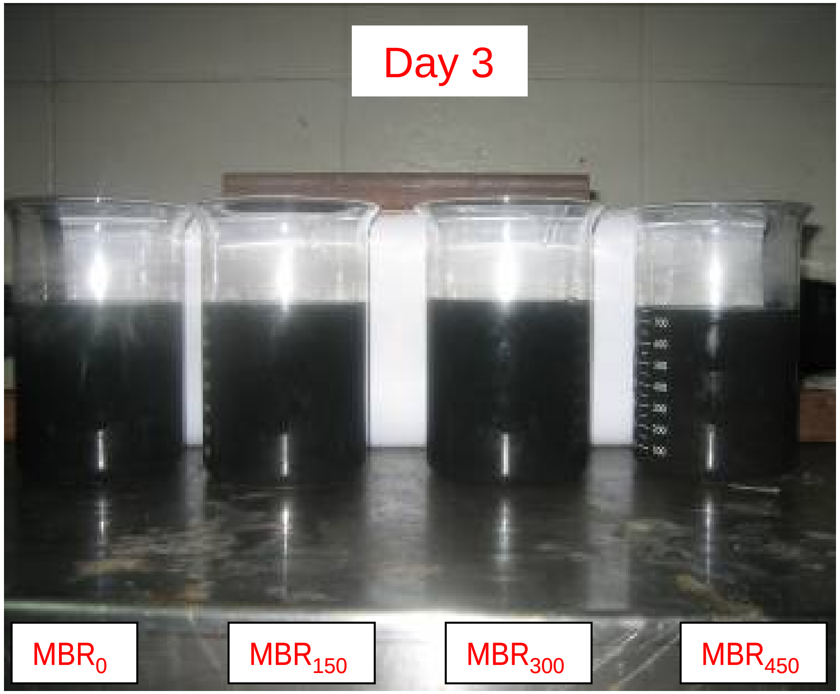
- Simulated biofilms of MBRs changed color from yellow to brown, then gray and ultimately black with time under limited transfer of oxygen and substrate;
- Change of color indicated bacterial condition from yellow (alive) to black (dead).

Page 60

Results and Discussion: Phase I

Simulation of biopolymers in biofilm (5-day period)



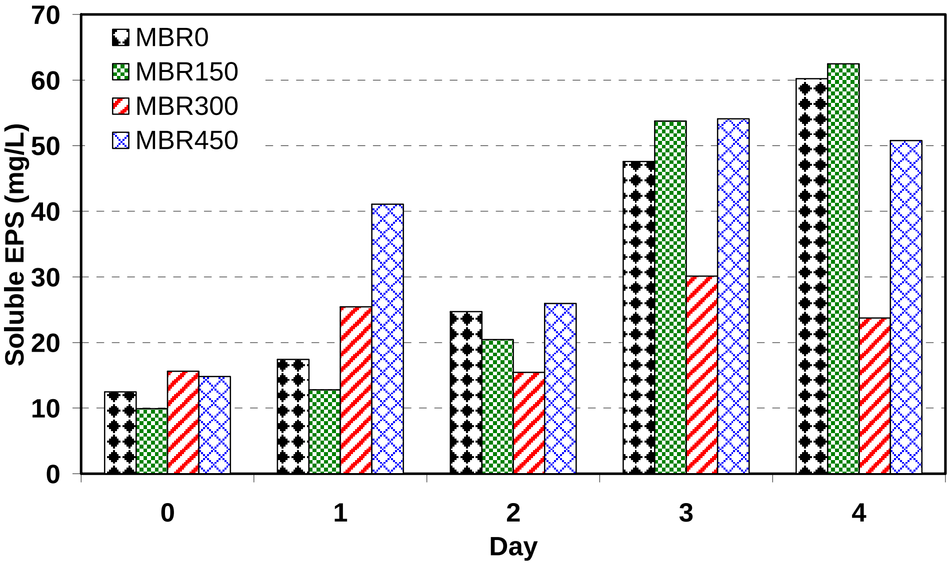


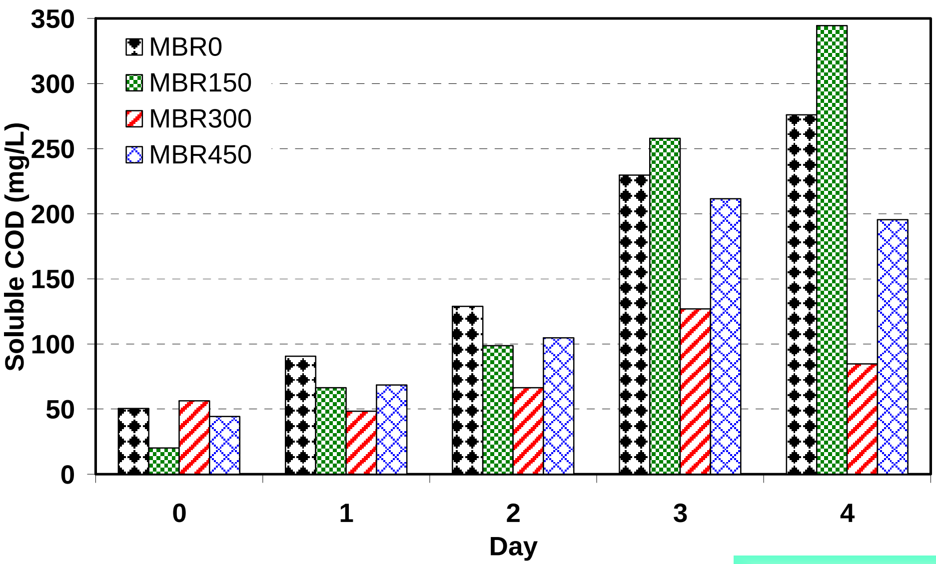
- Bacterial death rate was faster in MBR_0 and MBR_{150} as compared to that in MBR_{300} and MBR_{450}.

Page 60

Results and Discussion: Phase I

Simulation of biopolymers in biofilm (5-day period)



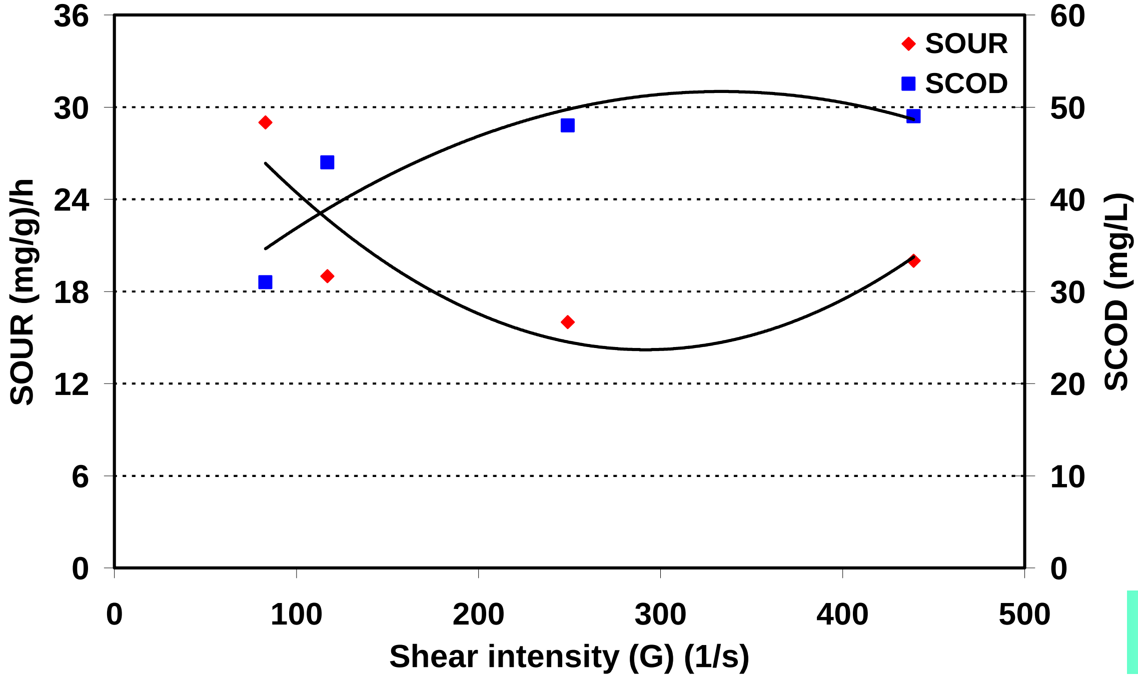


Page 61

- Biomass excreted high concentration of biopolymers in simulated biofilms after day 2;
- Protein content predominantly increased in excreted EPS after day 2 suggesting cell lysis due to bacterial death;
- Biopolymers excreted in MBR_{300} sludge sample were lowest followed by one in MBR_{450} sludge sample.

Results and Discussion: Phase I

SOUR and SCOD in MBRs



Page 130

- SOUR decreased with increase in shear intensity (G) with MBR_{300} sludge exhibiting lowest microbial activity;
- Decrease in SOUR (bioactivity) responsible for relative increase in SCOD in MBRs;
- However, decrease in bioactivity also responsible for slow bacterial death rate and subsequent lower biopolymer release within biofilm.

Results and Discussion: Phase II

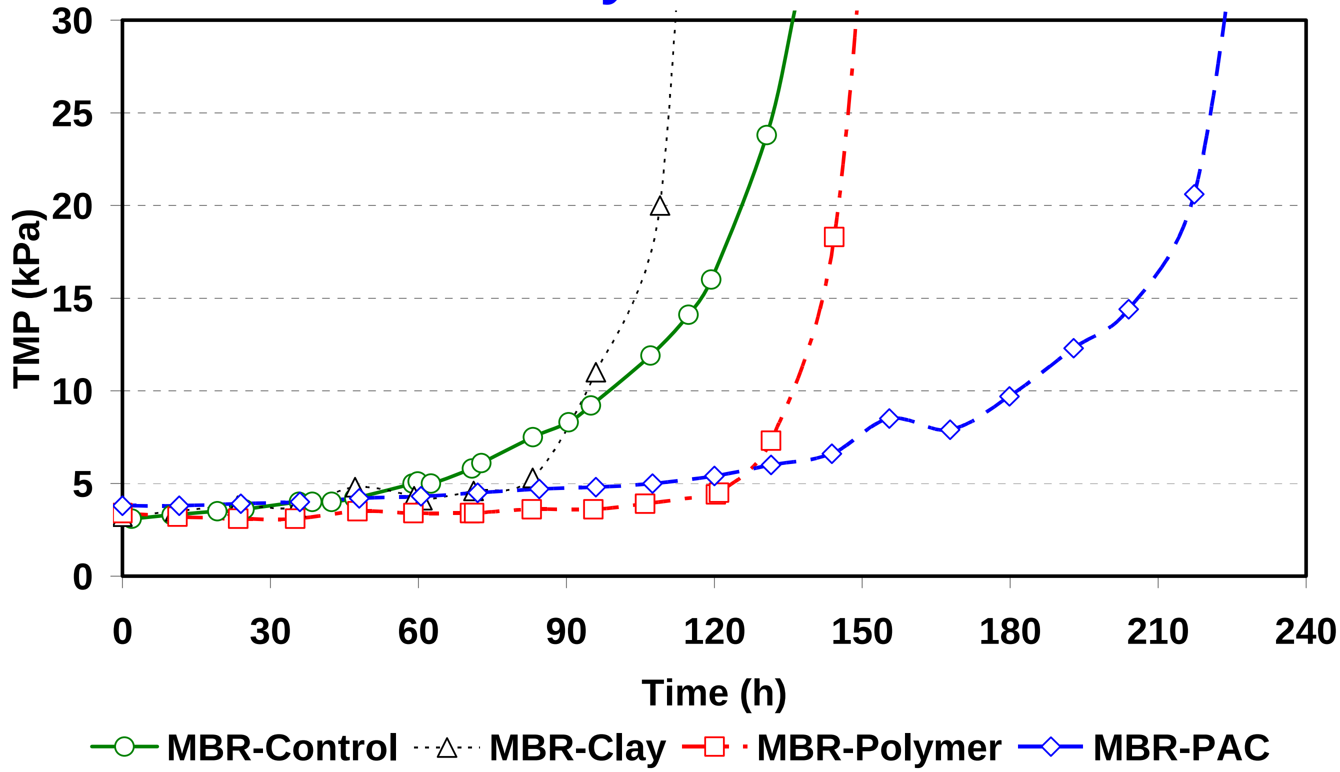
Flocculent/adsorbents initial dosage to hybrid MBRs

MBR	Size range/ solution condition	Initial dosage based on Jar test (mg/L)	Optimum dosage criterion
$MBR_{Control}$	No addition	-	-
MBR_{Clay}	Sieved (100-325 mesh)	1,000	Increase in settling ability
$MBR_{Polymer}$	Soluble in water	100	Decrease in SCOD
MBR_{PAC}	Sieved (100-325 mesh)	1,000	Decrease in SCOD

Daily dosage based on 40 d SRT

Results and Discussion: Phase II

Filtration behaviors in hybrid MBRs

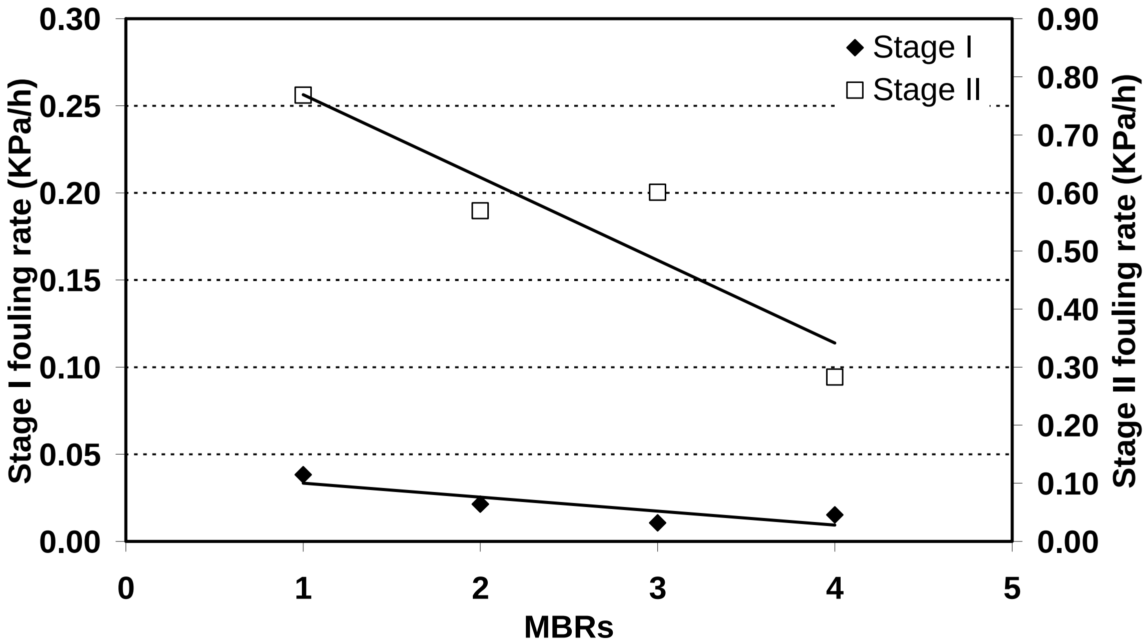


Page 70

- MBR_{Clay} fouled rapidly followed by $MBR_{Control}$ and $MBR_{Polymer}$ and lastly by $MBR_{PAC;}$
- MBR_{PAC} exhibited least fouling propensity due to PAC addition as it forms incompressible particulate layer of high permeability.

Results and Discussion: Phase II

Membrane fouling rates in hybrid MBRs



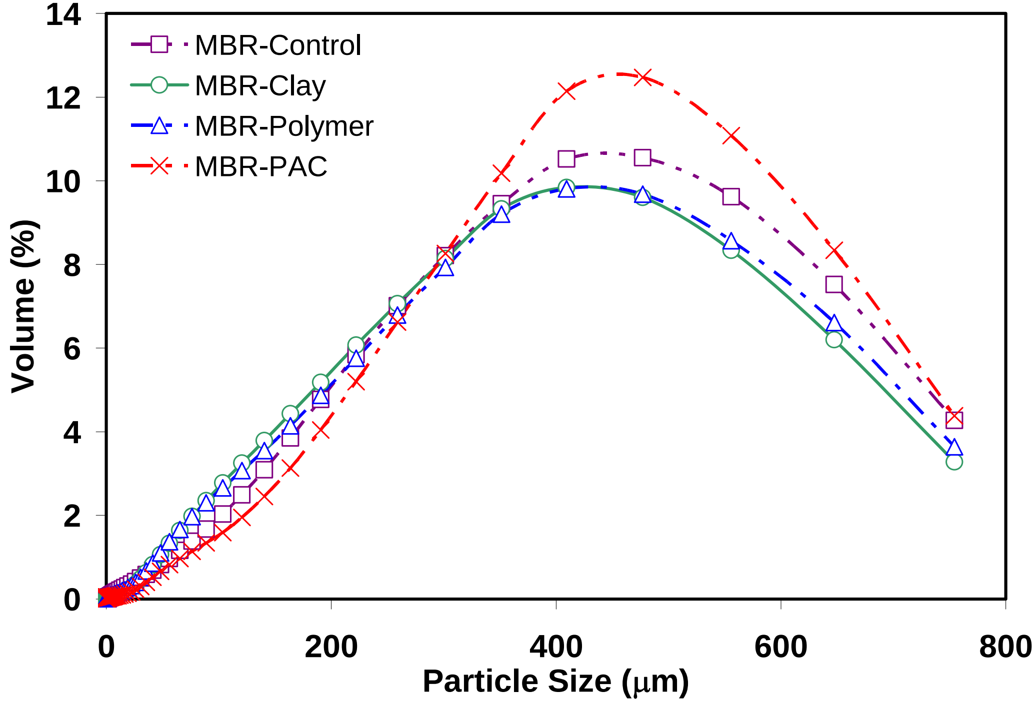
Page 72

MBRs: 1 = $MBR_{Control}$; 2 = MBR_{Clay}; 3 = $MBR_{Polymer}$; 4 = MBR_{PAC}

- Stage I fouling rate being relatively similar attributed to similar hydrodynamic conditions among the MBRs;
- However, 60% reduction observed in Stage II fouling rate of MBR_{PAC} as compared to that of $MBR_{Control}$.

Results and Discussion: Phase II

Particle size distributions (PSD) in hybrid MBRs



MBR	Particle size (μm)
MBR-Control	363
MBR-Clay	331
MBR-Polymer	336
MBR-PAC	401

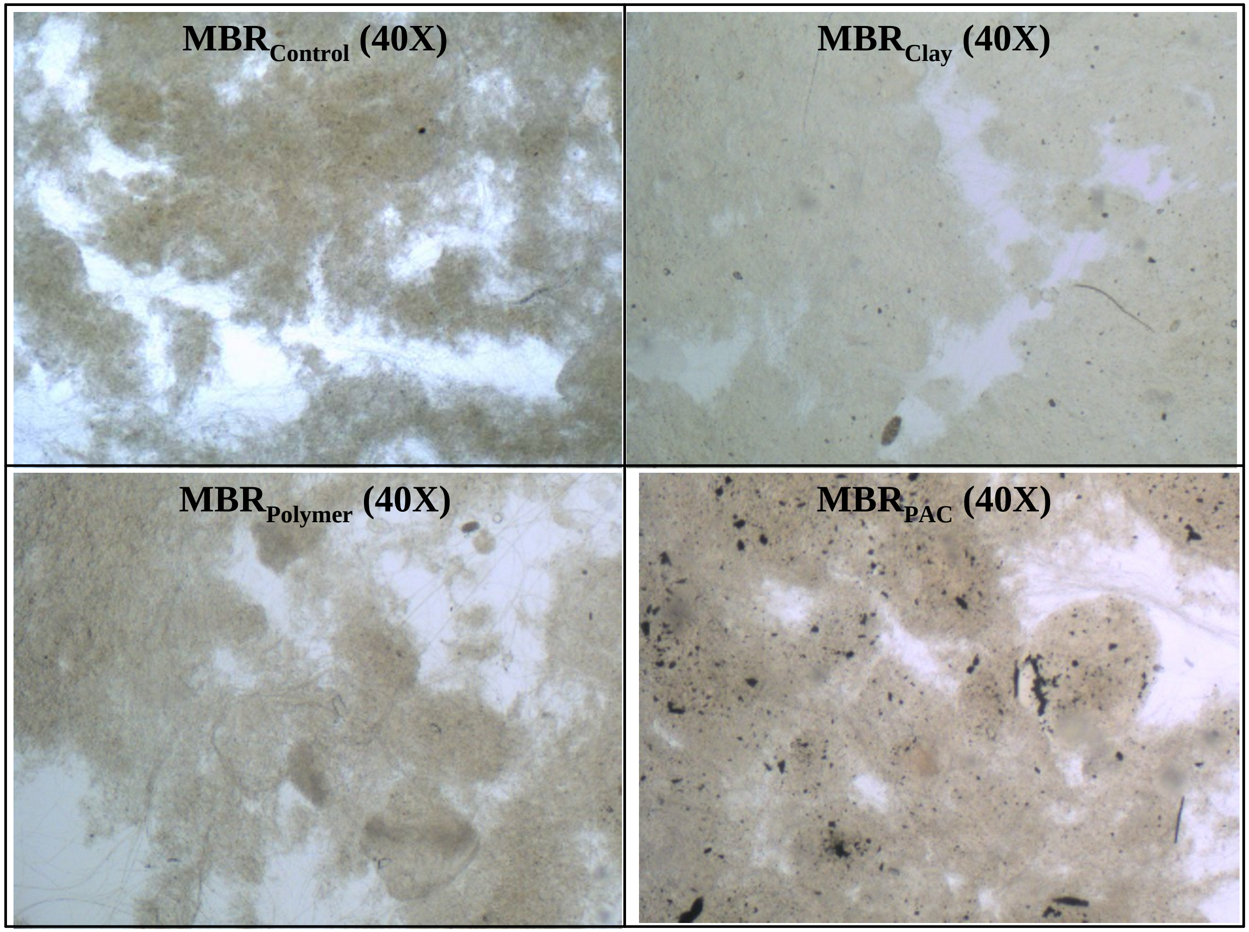
Page 75

- Percentage of large bio-particles (300-700 μm) by sludge volume higher in MBR_{PAC} as compared to that in other MBRs;
- MBR_{PAC} with large bio-particles could provide high cake layer porosity resulting in low fouling behavior.

Results and Discussion: Phase II

Sludge morphology in hybrid MBRs

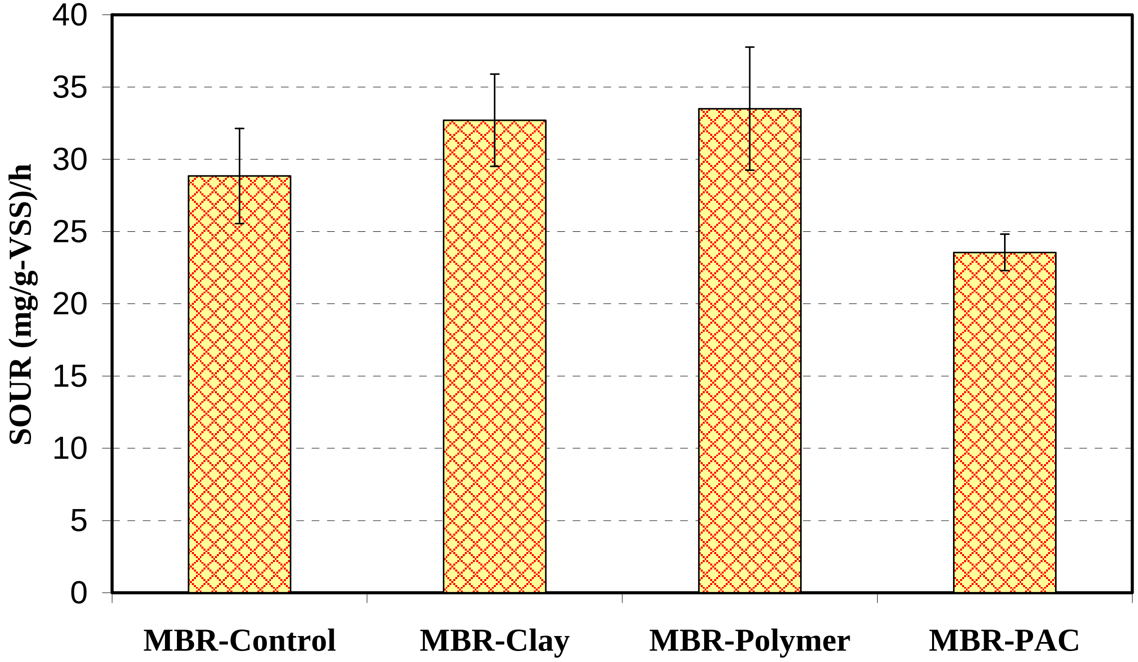
- Bio-flocs in MBR_{PAC} were more or less rounded and firm (incompressible) as PAC served as media for biofilm growth forming biologically activated carbon;
- Bio-flocs in other MBRs were irregular and weak (compressible).



Page 76

Results and Discussion: Phase II

SOUR in hybrid MBRs



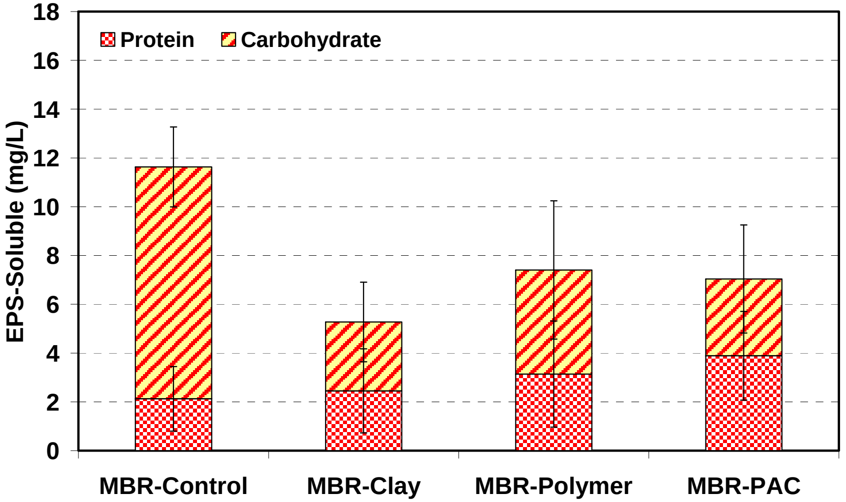
Page 77

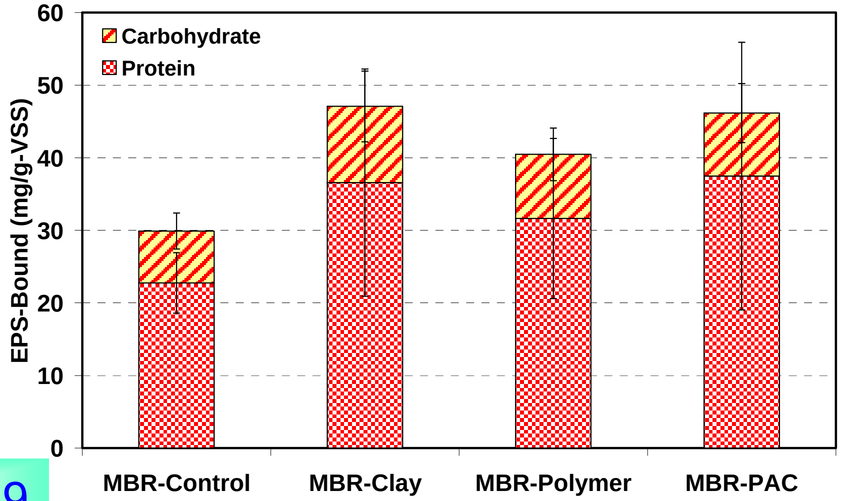
- On average, SOUR of 24 (mg/g-VSS)/h in MBR_{PAC} as compared to 29, 33 and 34 (mg/g-VSS)/h in $MBR_{Control}$, MBR_{Clay} and $MBR_{Polymer}$, respectively;
- PAC facilitating microbial attachment and biofilm growth could result in microbes imbedded inside biofilm and consequently lowering SOUR;
- Low SOUR and large bio-flocs could be basis of improved filtration performance in MBR_{PAC}.

Results and Discussion: Phase II

Soluble and bound EPS in hybrid MBRs

- Soluble EPS was reduced by about 50% in hybrid MBRs as compared to that in $MBR_{Control}$;
- Protein content almost remained constant while carbohydrate content decreased;
- Reduction in carbohydrate fraction of soluble EPS achieved by flocculation and adsorption phenomena;
- Bound EPS increased in hybrid MBRs as compared to that in $MBR_{Control}$;
- Soluble EPS entrapment led to high bound EPS levels;
- However, soluble and bound EPS variation had insignificant influence on fouling behaviors.





Page 78-79

Conclusion and Recommendations

Conclusion: Mechanically mixed MBRs (Phase I)

- Prolong filtration cycle in MBR_{300} operation as compared to that in other MBRs;
- Two distinct fouling stages during MBRs operation, slow gradual TMP rise followed by rapid TMP rise;
- High filterability of MBR_{300} sludge characterized by low CST_N and specific cake resistance (α);
- Size of bio-particles were stable in MBR_0, MBR_{150} and MBR_{300} i.e. from G value of 83 up to 249 s^{-1} beyond which bio-flocs broke to less than half the original size in MBR_{450} (G of 439 s^{-1});
- Fouling mitigation achieved in MBR_{300} attributed to high shear intensity and distribution over membrane fibers and to modification in sludge properties including reduction in SOUR of active biomass.

Conclusion and Recommendations

Conclusion: Hybrid MBRs (Phase II)

- Prolong filtration cycle in MBR_{PAC} operation as compared to that in other MBRs;
- Improved filtration performance in MBR_{PAC} attributed to flocculation and adsorption phenomena with biological activated carbon offering high cake permeability;
- Large and firm bio-flocs assisted by PAC addition offering incompressible cake layer in MBR_{PAC} as compared to relatively small and weak (compressible) bio-flocs in other MBRs;
- Low microbial activity (SOUR) in MBR_{PAC} as compared to that in other MBRs could also be responsible for improved filtration performance.

Conclusion and Recommendations

Recommendations

- Further investigation to improve Stage I fouling and avoid Stage II fouling by employing membrane regeneration techniques such as back washing during Stage I;
- Investigation pertinent to fiber density, bundle diameter and location of aerators for given aeration intensity in HF submerged MBRs;
- Up-scaling of laboratory-scale mechanically mixed MBR to pilot-scale MBR with optimum shear intensity and usage of real wastewater;
- Development of unified membrane fouling model considering first stage fouling as well as second stage fouling patterns.

Contribution to Membrane Technology

- Novel hydrodynamic technique for fouling mitigation in MBR process was introduced by providing mechanical mixing in addition to aeration. Filtration performance and sludge characteristics investigation led to determination of 300 rpm as optimum mixing rate.

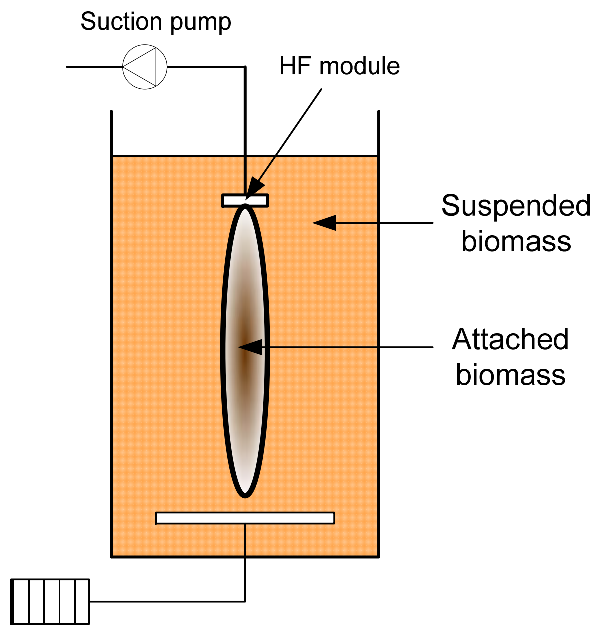
- Two-stage fouling pattern was extensively investigated. Fouling rates during two the stages were determined and discussed separately.

- Empirical fouling model was developed based on cake filtration theory taking into account reduction of fouling rate with increase in shear intensity (G). Moreover, model incorporated influence of specific cake resistance (α) on fouling rate (dR/dt).

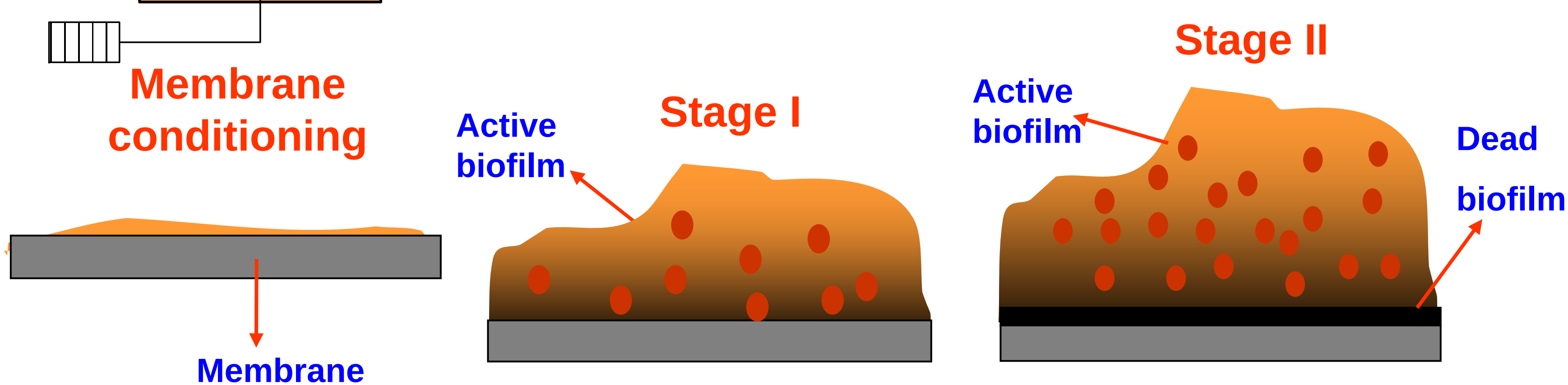
- Hybrid MBR developed with optimum dosage of PAC to bioreactor demonstrated prolong filtration performance. Low fouling rates in MBR_{PAC} were due to high cake layer porosity by incompressible large bio-flocs and adsorption of organic matter.

Contribution to Membrane Technology

➢ Bio-fouling phenomenon & mitigation in MBR process



MBR	SCOD (suspended) (mg/L)	SCOD (attached -Day 0) (mg/L)	SCOD (attached -Day 5) (mg/L)	SOUR (mg/g)/h
MBR_0	31	50	276	29
MBR_{300}	48	56	85	16



Publications

International publications

- Jamal Khan, S. and Visvanathan, C. Influence of mechanical mixing intensity on a biofilm structure and permeability in a membrane bioreactor. Accepted for publication in journal ***Desalination***

- Jamal Khan, S., Visvanathan, C., Jegatheesan, V. and Ben Aim, R. Influence of mechanical mixing rates on sludge characteristics and membrane fouling in MBRs. Accepted for publication in journal ***Separation Science and Technology***

Thank you

for your attention