

Adsorption – Filtration Hybrid System in Wastewater Treatment and Reuse

By

Durgananda Singh Chaudhary

M. Engg. (Environmental Engineering)

Asian Institute of Technology, Bangkok, Thailand



Submitted in fulfillment for the degree of

Doctor of Philosophy

Faculty of Engineering

University of Technology, Sydney (UTS)

Australia

2003

CERTIFICATE

I certify that this thesis has not already been submitted for any degree and is not being submitted as part of candidature for any other degree.

I also certify that the thesis has been written by me and that any help that I have received in preparing this thesis, and all sources used, have been acknowledged in this thesis.

Signature of Candidate

Production Note:

Signature removed prior to publication.

ACKNOWLEDGEMENTS

I wish to express my profound gratitude and appreciation to my principal supervisor, Professor S. Vigneswaran for his invaluable suggestions, support, ideas, comments, and continuous guidance throughout the study. I also wish to express my deep gratefulness and appreciation to my other supervisor, Dr. H. H. Ngo for his great support, thoughts, encouragement, and guidance. This work would not have been completed without their thoughtful encouragements.

I sincerely thank Professor Roger Ben Aim, France, and Professor H. Moon, Korea for their invaluable comments and ideas.

I would like to thank Dr. V. Jegatheesan, Mr. S. H. Kim and W. G. Shim for their assistance in the mathematical modelling.

I like to thank all the staffs and friends at the Faculty of Engineering, University of Technology, Sydney (UTS). I will always remember Kwon, Mehdi, Ramesh, Wenshan, Cuong and Hugh for creating homely and pleasant environment during my stay at UTS. I also like to thank Anya Van Eeuwen and David Hooper for their help and support.

I am thankful to my wife Januka Chaudhary, daughter Nikita Singh Chaudhary, and son Nikhil Singh Chaudhary who provided me with joy and happiness, and made this work possible. I will be indebted throughout my life to my father Chumuk lal Chaudhary and mother Khuwain Chaudhary for their sacrifice in raising me to the present level. I also like to thank all my four brothers Prit Narayan Chaudhary, Mahendra Chaudhary, Surendra Chaudhary, and Manohar Chaudhary for their understandings and help during this study.

TABLE OF CONTENTS

Title page	i
Certificate	ii
Acknowledgements	iii
Dedication	iv
Table of contents	v
Nomenclature	xiii
List of the tables	xix
List of the figures	xxii
Extended abstract	xxxiii

Chapter 1

Introduction	1
1.1 Overview	1
1.1.1 Organics in wastewater: sources and problems	2
1.1.2 Treatment options for organic removal from wastewater	3
1.1.2.1 Adsorption	4
1.1.2.2 Biosorption or biofiltration	5
1.1.2.3 Adsorption-membrane hybrid system	7
1.1.3 Imperatives of the study	9
1.2 Objectives of the study	10
1.2.1 Adsorption Study	10
1.2.2 Biosorption or biofiltration study	11
1.2.3 Adsorption-membrane hybrid system	11

1.3	Scope of the study	12
1.3.1	Experimental	12
1.3.2	Mathematical modelling	13
1.4	Organization of the report	15

Chapter 2

Literature Review	16	
2.1	Introduction	16
2.2	Activated carbon adsorption in the advanced wastewater treatment	19
2.2.1	Adsorption mechanism	21
2.2.2	Adsorption kinetics and equilibrium	22
2.2.3	Factors affecting adsorption of organics	26
2.2.4	Past studies on adsorption	30
2.3	Biosorption and biodegradation of organics	39
2.3.1	Biosorption process	39
2.3.2	Biomass and its measurement techniques	41
2.3.2.1	Van der Kooij method	41
2.3.2.2	Kemmy et al. method	42
2.3.2.3	US-EPA method	42
2.3.2.4	Werner method	42
2.3.2.5	Jago-Stanfield method	43
2.3.2.6	Billen-Servais method	43
2.3.3	Past studies on biofiltration	44
2.4	Adsorption-membrane hybrid system for wastewater treatment	47
2.4.1	Membrane fundamentals	48
2.4.1.1	Membrane definition	48
2.4.1.2	Process definition	48
2.4.1.2.1	Permeate flux	49

2.4.1.2.2	Conversion or recovery	49
2.4.1.2.3	Rejection	49
2.4.2	Membrane separation process	50
2.4.2.1	Microfiltration (MF)	50
2.4.2.2	Ultrafiltration (UF)	51
2.4.2.3	Nanofiltration (NF)	51
2.4.2.4	Reverse osmosis (RO)	52
2.4.3	Membrane fouling	52
2.4.3.1	Organic fouling	53
2.4.3.2	Inorganic fouling or scaling	53
2.4.4	Membrane fouling control measures	54
2.4.4.1	Pretreatment for fouling prevention	54
2.4.4.2	Backwashing, backflushing and operation mode	55
2.4.4.3	Membrane cleaning	55
2.4.5	Past studies on adsorption-membrane hybrid system	56

Chapter 3

Adsorption Equilibria 57

3.1	Introduction	57
3.2	Adsorption isotherm	58
3.3	Association theory	63
3.4	Characterization theory	65
3.5	Experimental investigation	70
3.6	Results and discussion	71
3.6.1	Biodegradation of organics	72
3.6.2	Effects of inorganic substances on the overall adsorption isotherm	78
3.6.3	Adsorption equilibrium of individual organic component	83
3.6.4	Overall adsorption equilibrium of the synthetic wastewater	91
3.6.5	Overall adsorption equilibrium of the biologically treated sewage	

	effluent	96
3.6.6	Characterization of the wastewater	99
3.7	Conclusions	103

Chapter 4

	Adsorption Kinetics	104
4.1	Introduction	104
4.2	Mass transfer mechanism	105
4.2.1	External diffusion	105
4.2.2	Internal diffusion	108
	4.2.2.1 Surface diffusion model	108
	4.2.2.2 Pore diffusion model	109
	4.2.2.3 Combined diffusion model	110
4.3	Linear driving force approximation (LDFA) model	111
4.4	Experimental investigation	114
4.5	Results and discussion	115
4.5.1	Adsorption kinetics of individual component of the synthetic wastewater	117
4.5.2	Effect of GAC dose	120
4.5.3	Effect of mixing intensity (G)	125
4.5.4	Effect of initial organic concentration	130
4.6	Development of empirical relationship for the film mass transfer coefficient	132
4.7	Conclusions	133

Chapter 5

Fixed Bed Adsorption	134
5.1 Introduction	134
5.2 Adsorption dynamics of the fixed bed system	137
5.3 Axial dispersion coefficient	138
5.4 Mass transfer in the fixed bed adsorption system	140
5.5 Experimental investigation	142
5.6 Results and discussion	146
5.6.1 Sensitivity analysis of the dynamic model	146
5.6.2 Effect of bed depth	151
5.6.3 Effect of filtration rate	156
5.6.4 Effect of initial organic concentration	161
5.7 Conclusions	164

Chapter 6

Biological degradation of organics in granular activated carbon (GAC) biofilter	165
6.1 Introduction	165
6.1.1 Biofilter in wastewater treatment	165
6.1.2 Biofilter in drinking water treatment	166
6.2 Major factors influencing the performance of a biofilter	168
6.2.1 Filter media	168
6.2.2 Empty bed contact time (EBCT)	169
6.2.3 Backwashing	170

6.3	Fundamentals of biological processes in a biofilter	170
6.3.1	Attachment of microorganisms	171
6.3.2	Substrate utilization and biofilm growth	171
6.3.3	Detachment of biomass	175
6.4	Development of mathematical modelling	177
6.4.1	Substrate in the bulk liquid	187
6.4.2	Biomass suspended in the bulk liquid	188
6.4.3	Biofilm diffusion and biodegradation	189
6.4.4	Biofilm growth and decay	190
6.4.5	Support phase substrate balance	191
6.4.6	Change in bed porosity, specific surface area and bed depth	191
6.4.7	Sensitivity analysis of the model	193
6.4.8	Estimation of the model parameter	196
6.5	Experimental investigation	197
6.5.1	Biofilter parameters and its measurement	199
6.5.2	Estimation of the biomass growth	199
6.5.3	Long-term performance of the biofilter	204
6.5.4	Effect of filtration rate and influent organic concentration	207
6.6	Conclusions	211

Chapter 7

Adsorption-Membrane Hybrid System 212

7.1	Introduction	212
7.1.1	Application of membrane without PAC	213
7.1.2	Application of membrane with PAC	214

7.2	Microfiltration process	217
7.2.1	Permeate flux	217
7.2.2	Transmembrane pressure	218
7.2.3	Membrane fouling	222
7.3	Mathematical modelling of the microfiltration hybrid system	223
7.3.1	Flux decline and fouling models.	223
7.3.1.1	Cake filtration model (CFM)	224
7.3.1.2	Standard blocking model (SBM)	225
7.3.1.3	Intermediate blocking model (IBM)	225
7.3.1.4	Complete blocking model (CBM)	226
7.3.2	Adsorption model for the submerged membrane hybrid system	228
7.3.3	Sensitivity analysis of the adsorption dynamics model	233
7.4	Experimental investigation	239
7.4.1	Adsorption equilibrium with PAC	239
7.4.1.1	Experimental investigation	239
7.4.1.2	Results of the adsorption equilibrium study	240
7.4.2	Adsorption batch kinetics with PAC	243
7.4.2.1	Experimental Investigation	243
7.4.2.2	Results of the adsorption batch kinetics study	243
7.4.3	Experimental investigation of the submerged membrane-PAC Adsorption hybrid system	247
7.4.3.1	Membrane cleaning procedure	249
7.4.3.2	Effect of PAC dose on the effluent TOC profile	249
7.4.4	Experimental investigations of the external loop cross-flow Microfiltration system	256
7.4.4.1	Effect of PAC dose and the TMP on the permeate flux	258
7.4.4.2	Membrane fouling mechanisms	264
7.5	Conclusions	268

Chapter 8

Conclusions and Recommendations 270

8.1	Conclusions	270
8.1.1	Batch equilibrium adsorption study	270
8.1.2	Batch kinetics adsorption study	271
8.1.3	Fixed bed adsorption column system	272
8.1.4	Biofiltration system	272
8.1.5	Adsorption-membrane hybrid system	273
	8.1.5.1 External loop flat plate membrane	273
	8.1.5.2 Submerged hollow fibre membrane	274
8.2	Recommendations	275

References 276

Appendix 1

- (a) Effect of pre-flocculation (FeCl_2) on adsorption
- (b) Adsorption of organics in spiral mixing system

Appendix 2

Relationship between TOC, COD, and UV-210 & 260 of the wastewater

Appendix 3

Publications made from the study

NOMENCLATURE

a	=	Specific surface area (area per unit mass of adsorbent) (L^2M^{-1})
A	=	Surface area normal to the filter media (L^2)
a'_f	=	Specific surface area of the pellet with biomass (L^2M^{-1})
A_f	=	Biofilm surface area (L^2)
A_m	=	Membrane surface area perpendicular to the flow (L^2)
A_s	=	Surface area of the adsorbent (L^2)
b	=	Biofilm decay coefficient (T^{-1})
B_1	=	Biologically attached bacterial biomass (ML^{-3})
B_2	=	Reversibly adsorbed bacterial biomass (ML^{-3})
B_3	=	Free bacterial biomass in the liquid phase (ML^{-3})
BIO	=	Biodegradation by the microbial community
b_{max}	=	Maximum uptake rate of S (T^{-1})
b_s	=	Biofilm shear loss coefficient (T^{-1})
b_{tot}	=	First order biofilm detachment coefficient for decay and shear (T^{-1}).
b_{tot}	=	First order biofilm detachment coefficient for decay and shear (T^{-1}).
b_{tot}	=	Overall loss rate of biomass due to both decay and fluid shear (T^{-1})
b_{tot}	=	Total shear and decay loss (T^{-1})
C	=	Concentration of the adsorbate in solution phase (ML^{-3})
C_0	=	Initial Organic concentration in the feed tank (ML^{-3})
C_b	=	Organic concentration in the bulk phase in the reactor (ML^{-3})
C_e	=	Effluent concentration (ML^{-3})
C_i	=	Influent concentration (ML^{-3})
C_i	=	Liquid phase organic concentration of i^{th} species in the mixture (ML^{-3})
C_i^0	=	Single solute liquid phase concentration in equilibrium (ML^{-3})
C_{i0}	=	Initial liquid phase organic concentration of i^{th} component (ML^{-3})
C_p	=	Permeate organic concentration (ML^{-3})
C_r	=	$Q\beta$ concentration in the bulk phase (ML^{-3})

C_s	=	Concentration of the adsorbate in the liquid phase at the liquid-particle interface, (ML^{-3})
\bar{c}	=	Concentration density function of the solution phase
C_r^∞	=	Equilibrium concentration of $Q\beta$ in the bulk phase (ML^{-3})
C_T	=	Total liquid phase concentration (ML^{-3})
C_{Tcal}	=	Calculated liquid phase concentration (ML^{-3})
C_{Texp}	=	Experimental liquid phase concentration (ML^{-3})
C_{to}	=	Initial total liquid phase concentration (ML^{-3})
d	=	Fixed bed depth (L)
	=	Sweeping diameter of the impeller (L)
D	=	Molecular diffusion coefficient for the substrate in the bulk liquid phase (L^2T^{-1})
D'	=	Dispersion coefficient (L^2T^{-1})
D_f	=	Substrate diffusion coefficient in the biofilm (L^2T^{-1})
D_m	=	Molecular diffusion coefficient (L^2T^{-1})
D_s	=	Effective surface diffusion coefficient of adsorbate (L^2T^{-1})
D_{si}	=	Surface diffusion coefficient (D_{si}) of the i^{th} component (L^2T^{-1})
$e_{i(max)}$	=	Maximum rate of H_i hydrolysis (T^{-1})
F	=	Object function (%)
g_c	=	Gravity conversion coefficient (LT^{-2})
H	=	Adsorption constant (Henry's Law constant)
H_i	=	Macromolecular organic matter of utilization class i (ML^{-3})
J_0	=	Initial flux rate ($L^3L^{-2}T^{-1}$)
J_f	=	Flux of substrate into the biofilm ($ML^{-2}T^{-1}$)
J_p	=	Permeate flux ($L^3L^{-2}T^{-1}$)
K	=	Reaction constant
k	=	Maximum specific rate of substrate utilization ($MM^{-1}T^{-1}$)
	=	First order reaction coefficient (T^{-1})
k''_d	=	Detachment rate coefficient (ML^{-3})
k'_d	=	Detachment rate coefficient ($ML^{-3}T^{-1}$)

k_a	=	Coefficient for adsorption onto PAC
k_{ads}	=	Adsorption constant for bacteria ($M^{-1}L^3T$)
k_c	=	Cake formation filtration constant
k_{ct}	=	Complete blocking filtration constant
k_d	=	Coefficient for the bacterial decay (T^{-1})
k_{des}	=	Desorption constant for bacteria (T^{-1})
k_e	=	Coefficient for inactivation due to the desorption of $Q\beta$ from PAC
K_F	=	Freundlich adsorption coefficient
k_f	=	Liquid-film mass transfer coefficient, (LT^{-1})
K_{Hi}	=	Half saturation constant for H_i hydrolysis, (ML^{-3})
k_i	=	Freundlich constant for i^{th} component
	=	Intermediate blocking filtration constant
k_m	=	Coefficient for attachment to the membrane
k_{max}	=	Maximum rate of substrate utilization, mg/mg/s
k_p	=	Particle phase mass transfer coefficient, (LT^{-1})
K_s	=	Monod half saturation coefficient (ML^{-3})
k_s	=	Solid phase mass transfer coefficient (LT^{-1})
	=	Standard blocking filtration constant
	=	Scale factor
L	=	Bed depth (L)
L_d	=	Diffusion layer thickness (L)
L_f	=	Biofilm thickness (L),
L_o	=	Initial bed depth (L)
M	=	Weight of the adsorbent (M)
M_b	=	Molecular weight of the solvent (M)
MCC	=	Membrane correlation coefficient,
M_p	=	Weight of the adsorbent (M)
n	=	Freundlich exponential coefficient
	=	Rotation speed (T^{-1})
N	=	Substrate uptake rate of the biofilm ($ML^{-2}T^{-1}$)
	=	Number of data points
N_p	=	Power number

P	=	Input power to the fluid (MLT^{-1})
P_C	=	Average concentrate pressure (Pa)
P_F	=	Average feed pressure (Pa)
P_p	=	Average permeate pressure (Pa)
\bar{q}	=	Average adsorbed phase concentration (MM^{-1})
Q	=	Flow rate (L^3T^{-1})
q	=	Surface concentration of adsorbed substrate (MM^{-1})
q_i^0	=	Adsorbed phase concentration in single solute state (MM^{-1})
q_m	=	Maximum specific rate of substrate utilization ($MM^{-1}T^{-1}$)
	=	Saturation amount of organic adsorbed (MM^{-1})
q_o	=	Initial adsorbed phase concentration (MM^{-1})
Q_p	=	Permeate flow (L^3T^{-1})
q_s	=	Equilibrium adsorbed phase organic concentration (MM^{-1})
q_t	=	Total solid phase organic concentration (MM^{-1})
q_w	=	Surface concentration at biofilm/activated carbon interface
r	=	Radial distance measured from the center of the pellet (L)
R	=	Radium of the carbon particle (L)
r_{diff}	=	Rate for substrate accumulation due to diffusion ($ML^{-3}T^{-1}$)
R_e	=	Total external resistance ($= R_p + R_f$)
REM	=	Fraction of biomass removed by backwashing
R_f	=	External fouling resistance formed by deposited cake layer
r_f	=	Radial coordinate in the biofilm (L)
r_{gr}	=	Rate of biomass growth within the biofilm (MT^{-1})
R_i	=	Internal resistance due to adsorbed substances into the pores
r_{loss}	=	Rate of loss of biomass (MT^{-1})
R_m	=	Intrinsic membrane resistance
R_p	=	Adsorbent particle radius (L)
	=	Polarization layer resistance caused by the concentration gradient
r_s	=	Radial coordinate in activated carbon (L)
R_T	=	Total resistance to the filtration,

r_{util}	=	Rate of substrate utilization in the biofilm ($\text{ML}^{-3}\text{T}^{-1}$)
S	=	Substrate concentration (ML^{-3})
S_B	=	Maximum adsorption capacity for bacteria (ML^{-3})
S_b	=	Substrate concentration in the bulk liquid (ML^{-3})
S_f	=	Substrate concentration in the biofilm (ML^{-3}),
S_{min}	=	Minimum substrate concentration (ML^{-3})
SP	=	Maximum capacity for biological bacterial fixation (ML^{-3})
S_s	=	Substrate concentration at liquid/biofilm interface (ML^{-3})
T	=	Temperature, $^{\circ}\text{C}$
t	=	Time (T)
TOC	=	Total organic carbon (ML^{-3})
v	=	Fluid filtration velocity (LT^{-1})
V	=	Volume of the solute, fluid, or reactor (L^3)
V_M	=	Volume of the membrane (L^3)
W	=	Weight of adsorbent (M)
x	=	Distance along the biofilter length (L)
X_f	=	Cell density of biofilm (ML^{-3})
X_s	=	Suspended biomass concentration (ML^{-3})
X_{susp}	=	Suspended cell concentration (ML^{-3})
Y	=	Biomass growth yield factor
Z	=	Distance normal to the biofilm surface (L)
z_i	=	Mole fraction of the i^{th} species in the adsorbed phase

ε	=	Bed porosity
ε'	=	Bed porosity with biofilm
ε_0	=	Initial bed porosity
σ	=	Biofilm shear loss coefficient (T^{-1})
ψ	=	Organic concentration spreading parameter
ξ	=	Void fraction

μ	=	Viscosity of the fluid ($\text{ML}^{-1} \text{T}^{-1}$)
μ_g	=	Specific biomass growth rate (T^{-1})
μ_{gave}	=	Average specific biomass growth rate (T^{-1})
ϕ	=	Association factor of the solvent
θ	=	Empty bed contact time (T)
β	=	Filtration efficiency
ΔP	=	Transmembrane pressure (Pa)
ρ_p	=	Particle density of adsorbent (ML^{-3})
ρ	=	Density of the fluid (ML^{-3})

LIST OF TABLES

Table 1.1	Composition of secondary effluent of domestic wastewater from activated sludge process (Manka et al., 1974).
Table 1.2	Framework of the scope of the work of the research.
Table 2.1	Water reuse from STPs in Australia in 2000 (Dillon, 2001).
Table 2.2	Categories of municipal wastewater reuse (after US EPA, 1992).
Table 2.3	Basic types of industrial adsorbents (Dabrowski, 2001).
Table 2.4	Summary of the past studies on biofilter.
Table 2.5	Particle size range of membrane separation process (after Johns, 2000).
Table 3.1	Isotherms for single component adsorption system.
Table 3.2	Isotherms for multicomponent adsorption system.
Table 3.3	Constituents of the synthetic wastewater used.
Table 3.4	Physical properties of the GAC and PAC used in the study.
Table 3.5.	Biodegradation of the synthetic wastewater at different organic concentrations.
Table 3.6	Isotherm results of individual component with and without inorganics
Table 3.7	Isotherm parameters of the synthetic wastewater.
Table 3.8	Isotherm parameters of the biologically treated sewage effluent.

Table 3.9	Characterization results of the wastewater with GAC.
Table 4.1	Effect of inorganic compounds on the mass transfer coefficients of the synthetic wastewater.
Table 4.2	Mass transfer coefficients in the synthetic wastewater with an initial average TOC of 7 mg/L (Mixing intensity, $G = 92 \text{ s}^{-1}$ corresponding to the rotational speed of 100 rpm).
Table 4.3	Mass transfer coefficients in the synthetic wastewater with an initial average TOC of 4.7 mg/L (Mixing intensity, $G = 92 \text{ s}^{-1}$ corresponding to the rotational speed of 100 rpm).
Table 4.4	Mass transfer coefficients in the secondary treated effluent with an initial average TOC of 3.1 mg/L (Mixing intensity, $G = 92 \text{ s}^{-1}$ corresponding to the rotational speed of 100 rpm).
Table 4.5	Mass transfer coefficients in the synthetic wastewater at different mixing intensities (GAC dose = 1 g/L, average initial TOC = 7.0 mg/L).
Table 4.6	Mass transfer coefficients in the secondary treated effluent at different mixing intensities (GAC dose = 1 g/L, average initial TOC = 4.4 mg/L).
Table 4.7	Mass transfer coefficients in the synthetic wastewater (GAC dose = 1 g/L, mixing intensity = 92 s^{-1}).
Table 5.1	Constituents of the synthetic wastewater used.
Table 5.2	Physical properties of the GAC used in the study.
Table 5.3	Effect of bed depth on the film mass transfer coefficient of the fixed bed adsorption.

Table 5.4	Effect of filtration rate on the film mass transfer coefficient of the fixed bed adsorption.
Table 5.5	Effect of initial TOC concentration on the mass transfer coefficient of the fixed bed adsorption.
Table 6.1	Detachment rate expressions (after Hozalski, 1996)
Table 6.2.	Biofilm parameters of the model.
Table 6.3	Physical properties of GAC used.
Table 6.4	Constituents of the synthetic wastewater used.
Table 7.1	Isotherm parameter values.
Table 7.2	Properties of the membrane.
Table 7.3	Percentage error of the model prediction.

LIST OF FIGURES

- Figure 1.1 Schematic representation of GAC adsorption-biosorption or biofiltration process.
- Figure 1.2 Typical treatment scheme of adsorption-biofiltration system.
- Figure 1.3 External loop flat-plate membrane and submerged hollow fibre membrane hybrid systems.
- Figure 1.4 Typical treatment scheme of submerged adsorption-membrane hybrid system.
- Figure 2.1 The mass transfer mechanisms in GAC (Hand et al., 1983).
- Figure 2.2 Effect of carbon particle size on the adsorption isotherm of humic acid (Weber et al., 1983)
- Figure 2.3 Effect of pH on the adsorption isotherm of humic acid (Weber et al., 1983)
- Figure 2.4 Effect of background solution on the adsorption of humic acid (Weber et al., 1983)
- Figure 2.5 Effects of initial organic concentration on the adsorption isotherm of humic acid (Weber et al., 1983)
- Figure 2.6 An A-n network used to represent a solution with multiple solutes (Kage and Tien, 1987).

- Figure 2.7 Extent of adsorption for a solution containing several adsorbates of equal amount but with different adsorption affinity (Frick and Sontheimer, 1983).
- Figure 2.8 Integral batch adsorption of humic acid (Frick and Sontheimer, 1983).
- Figure 2.9 Freundlich constant (K) distribution of organics (Yuasa et al., 1996a).
- Figure 2.10 The overall adsorption isotherm of the biological process effluent effluent (Yuasa et al. 1996a).
- Figure 2.11 Clusters of the solutes around adsorption site in the association theory (Talu and Meunier, 1996).
- Figure 2.12 Typical idealized performance of activated carbon fixed bed with and without biological activity (C = effluent organic concentration, C_0 = influent organic concentration).
- Figure 2.13 Schematic of the membrane process (Q = flow, m^3/s ; C = concentration of the pollutants to be removed, mg/L ; O, P, and R refer to influent, permeate and retentate respectively).
- Figure 3.1 Types of pure component gas adsorption Isotherms in the classification of Brunauer, Emmett, and Teller (BET) (Brunauer et al., 1940).
- Figure 3.2 Biodegradation of the individual component without inorganics
- Figure 3.3 Biodegradation of the individual component with inorganics
- Figure 3.4 Biodegradation of the binary mixture of the organics with inorganics

- Figure 3.5 Biodegradation of the synthetic wastewater with and without inorganics
- Figure 3.6 Equilibrium isotherm of glucose with and without inorganic compounds
- Figure 3.7 Equilibrium isotherm of peptone with and without inorganic compounds
- Figure 3.8 Equilibrium isotherm of yeast extract with and without inorganic compounds
- Figure 3.9 Overall adsorption isotherm with and without inorganic compounds (Average initial TOC concentration = 3.3 mg/L)
- Figure 3.10 Equilibrium isotherm of yeast extract
- Figure 3.11 Equilibrium isotherm of peptone
- Figure 3.12 Equilibrium isotherm of glucose
- Figure 3.13 Equilibrium isotherm of glucose with inorganic compounds
- Figure 3.14 Equilibrium isotherm of peptone with inorganic compounds
- Figure 3.15 Equilibrium isotherm of yeast extract with inorganic compounds
- Figure 3.16 Overall adsorption isotherm at initial TOC concentration of 3.5 mg/L
- Figure 3.17 Overall adsorption isotherm at initial TOC concentration of 6.4 mg/L
- Figure 3.18 Overall adsorption isotherm at initial TOC concentration of 11.2 mg/L

- Figure 3.19 Effect of initial TOC concentration on isotherm parameters of association theory
- Figure 3.20 Overall adsorption isotherm of the biologically treated sewage effluent (Initial TOC = 3.7 mg/L)
- Figure 3.21 Prediction of integral adsorption equilibrium by characterization technique
- Figure 3.22 Concentration distribution fractions for the synthetic and the biologically treated sewage effluent
- Figure 4.1 Mass transfer steps in adsorption process
- Figure 4.2 Schematics of the batch experimental set-up (Speed controller 0-100 rpm, beaker 1 L)
- Figure 4.3 Batch adsorption of individual organic component in the absence of inorganic compounds of the synthetic wastewater (GAC dose = 5 g/L, rotational speed = 100 rpm, mixing intensity, $G = 92 \text{ s}^{-1}$, $C_{0(\text{glucose})} = 2.2 \text{ mg/L}$, $C_{0(\text{yeast})} = 1.3 \text{ mg/L}$, $C_{0(\text{peptone})} = 1.4 \text{ mg/L}$, C_o = initial organic concentration of individual organic compound)
- Figure 4.4 Batch adsorption of individual organic component in the presence of inorganic compounds of the synthetic wastewater (GAC dose = 5 g/L, rotational speed = 100 rpm, mixing intensity, $G = 92 \text{ s}^{-1}$, $C_{0(\text{glucose})} = 4.2 \text{ mg/L}$, $C_{0(\text{yeast})} = 2.1 \text{ mg/L}$, $C_{0(\text{peptone})} = 2.2 \text{ mg/L}$)
- Figure 4.5 Effect of GAC dose mass transfer rate in the synthetic wastewater with an initial average TOC of 7.0 mg/L (Mixing intensity, $G = 92 \text{ s}^{-1}$)
- Figure 4.6 Effect of GAC dose mass transfer rate in the synthetic wastewater with an initial average TOC of 4.7 mg/L (Mixing intensity, $G = 92 \text{ s}^{-1}$)

- Figure 4.7 Effect of GAC dose mass transfer rate in the secondary treated effluent with an initial average TOC of 3.1 mg/L (Mixing intensity, $G = 92 \text{ s}^{-1}$)
- Figure 4.8 Relationship between rotational speed and mixing intensity (Kawamura, 2000)
- Figure 4.9 Effect of mixing intensity on mass transfer rate in the synthetic wastewater (GAC dose = 1 g/L, average initial TOC = 7.0 mg/L)
- Figure 4.10 Effect of mixing intensity on mass transfer rate in the biologically treated sewage effluent (GAC dose = 1 g/L, average initial TOC = 4.4 mg/L)
- Figure 4.11 Effect of initial organic concentration on mass transfer rate in the synthetic wastewater (GAC dose = 1 g/L, mixing intensity = 92 s^{-1})
- Figure 5.1 Schematic representations of breakthrough curves: (a) poorly adsorbed case, (b) commonly observed adsorption case, and (c) strongly adsorbed case with on mass-transfer effect (after Tien, 1994)
- Figure 5.2 Schematic diagram of the fixed bed adsorption system
- Figure 5.3 Effect of film mass transfer coefficient on the breakthrough curve of the fixed bed adsorption system (Fixed bed depth = 4 cm, filtration velocity = 1 m/h, axial dispersion coefficient (D_L) = $1 \times 10^{-7} \text{ m}^2/\text{s}$, TOC = 6.9 mg/L)
- Figure 5.4 Effect of film mass transfer coefficient on the breakthrough curve of the fixed bed adsorption system (Fixed bed depth = 4 cm, filtration velocity = 5 m/h, axial dispersion coefficient (D_L) = $1 \times 10^{-5} \text{ m}^2/\text{s}$, TOC = 3.8 mg/L)
- Figure 5.5 Effect of axial dispersion coefficient on the breakthrough curve of the fixed bed adsorption system (Fixed bed depth = 4 cm, filtration

velocity = 1 m/h, Film mass transfer coefficient (k_f) = 1×10^{-6} m/s,
TOC = 6.9 mg/L)

Figure 5.6 Effect of axial dispersion coefficient on the breakthrough curve of the fixed bed adsorption system (Fixed bed depth = 4 cm, filtration velocity = 5 m/h, Film mass transfer coefficient (k_f) = 1×10^{-6} m/s, TOC = 3.8 mg/L)

Figure 5.7 Effect of the bed depth on effluent quality from the fixed bed system (Filtration rate = 5 m/h, average initial TOC of the synthetic wastewater = 7.5 mg/L)

Figure 5.8 Effect of the bed depth on effluent quality from the fixed bed system (Filtration rate = 1 m/h, average initial TOC of the synthetic wastewater = 4.0 mg/L)

Figure 5.9 Effect of bed depth on the effluent quality of the fixed bed system (Filtration rate = 7 m/h, average initial TOC of the biologically treated sewage effluent = 3.9 mg/L)

Figure 5.10 Effect of filtration rate on the effluent quality of the fixed bed system (Bed depth = 20 cm, average initial TOC of the synthetic wastewater = 7.0 mg/L)

Figure 5.11 Effect of filtration rate on the effluent quality of the fixed bed system (Bed depth = 4 cm, average initial TOC of the synthetic wastewater = 3.7 mg/L)

Figure 5.12 Effect of filtration velocity on the effluent quality of the fixed bed system (Bed depth = 4 cm, average initial TOC of the biologically treated sewage effluent = 4.3 mg/L)

- Figure 5.13 Effect of initial organic concentration of the synthetic wastewater on the effluent quality of the fixed bed system (Bed depth = 20 cm, filtration velocity = 10 m/h).
- Figure 5.14 Effect of initial organic concentration of the synthetic wastewater on the effluent quality of the fixed bed system (Bed depth = 4 cm, filtration velocity = 1 m/h)
- Figure 6.1 Idealized biofilm and characteristic deep, shallow, and fully penetrated profiles of the substrate concentration (after Rittmann, 1995)
- Figure 6.2 Effect of initial biofilm thickness (L_f) on the effluent organic concentration. ($X_s = 1.0E-7$ mg/L, $K_d = 5.0E-6$ s⁻¹, $\sigma = 1.16E-6$ 1/s, $\beta = 10000$, $Y = 0.34$ mg/mg, and $X_f = 6.44E+3$ mg/L)
- Figure 6.3 Effect of decay coefficient (K_d) on the effluent organic concentration. ($X_s = 1.0E-7$ mg/L, $L_f = 1.0E-6$ m, $\sigma = 1.16E-6$ s⁻¹, $\beta = 10000$, $Y = 0.34$ mg/mg, and $X_f = 6.44E+3$ mg/L)
- Figure 6.4 Biomass accumulation in the GAC biofilter (Filtration rate = 1 m/h, GAC = 5 g, average influent TOC = 3.5 mg/L)
- Figure 6.5 TOC removal efficiency of the GAC biofilter and model prediction (Filtration rate = 1 m/h, filter depth = 4 cm, average influent TOC = 3.50 mg/L) ($X_s = 1.0E-8$ mg/L, $L_f = 1.0E-6$ m, $\sigma = 1.16E-6$ s⁻¹, $\beta = 10000$, $Y = 0.34$ mg/mg, $X_f = 1.44E+3$ mg/L, and $K_d = 5.0E-6$ s⁻¹)
- Figure 6.6 Effect of filtration rate on the performance of GAC biofilter after acclimatization period (Acclimatization period = 77 days at 1 m/h, Average influent TOC = 3.5 mg/L, GAC = 5 g, C and C_o are the effluent and influent TOC concentration)

- Figure 6.7 Effect of influent organic concentration on the performance of GAC biofilter after acclimatization period (Acclimatization period = 77 days at 1 m/h, Filtration rate = 1 m/h, GAC = 5 g)
- Figure 7.1 Membrane separation process compared to other treatment processes, and solute / particle dimension (after Schafer, 2001)
- Figure 7.2a Illustration of flow patterns, flux decline, filter cake formation, and transmembrane pressures in dead-end filtration and crossflow filtration (after Ripperger, 1989 and Gunder, 2001)
- Figure 7.2b Variation of permeate flux with time (after Vigneswaran et al., 1991)
- Figure 7.3 Different particle retention mechanisms (Vigneswaran et al., 1991)
- Figure 7.4 Effect of membrane correlation coefficient on the effluent TOC (PAC dose = 200 mg/L, Influent TOC = 2.6 mg/L, $k_s = 1.6E-6$ m /s, filtration flux = 3×10^{-3} L/s/m², $K_f = 13.2$, $1/n = 1.5$, C = effluent TOC concentration, mg/L and C_0 = influent TOC concentration, mg/L)
- Figure 7.5 Effect of solid mass transfer rate (k_s) on the effluent TOC (PAC dose = 200 mg/L, Influent TOC = 2.6 mg/L, MCC = $3.9E-9$ m /s, filtration flux = 3×10^{-3} L/s/m², $K_f = 13.2$, $1/n = 1.5$, C = effluent TOC concentration, mg/L and C_0 = influent TOC concentration)
- Figure 7.6 Effect of filtration flux on the effluent TOC (PAC dose = 200 mg/L, Influent TOC = 2.6 mg/L, MCC = 3.8×10^{-9} m /s, $k_s = 1.6 \times 10^{-6}$ m/s, $K_f = 13.2$, $1/n = 1.5$, C = effluent TOC concentration, mg/L and C_0 = influent TOC concentration)

- Figure 7.7 Effect of Influent TOC concentration on the effluent TOC (PAC dose = 200 mg/L, Filtration flux = 3×10^{-3} L/s/m², MCC = 3.9×10^{-9} m /s, $k_s = 1.6 \times 10^{-6}$ m/s, $K_f = 13.2$, $1/n = 1.5$, C = effluent TOC concentration, mg/L and C_0 = influent TOC concentration)
- Figure 7.8 Overall adsorption isotherm of the synthetic wastewater at three different initial organic concentrations
- Figure 7.9 Overall adsorption isotherm of the biologically treated sewage effluent (Initial TOC = 3.5 mg/L)
- Figure 7.10 Mass transfer at different PAC doses (Mixing intensity, $G = 92$ s⁻¹, average initial TOC concentration of the synthetic wastewater = 3.8 mg/L, C = effluent TOC concentration, mg/L and C_0 = influent TOC concentration)
- Figure 7.11 Mass transfer at different PAC doses (Mixing intensity, $G = 92$ s⁻¹, average initial TOC concentration of the secondary sewage = 3.6 mg/L, C = effluent TOC concentration, mg/L and C_0 = influent TOC concentration)
- Figure 7.12 Schematic diagram of submerged hollowfibre membrane filtration hybrid system
- Figure 7.13 Effect of PAC dose on the performance of the submerged membrane (Filtration flux = 3×10^{-3} L/s/m², average influent TOC of biologically treated sewage effluent = 2.9 mg/L, C = effluent TOC concentration, mg/L and C_0 = influent TOC concentration)
- Figure 7.14 Effect of PAC dose on the performance of the submerged membrane (Filtration flux = 1.7×10^{-3} L/s/m², average influent TOC of the biologically treated sewage effluent = 3.0 mg/L, C = effluent TOC concentration, mg/L and C_0 = influent TOC concentration)

- Figure 7.15 Effect of PAC dose on the performance of the submerged membrane (Filtration flux rate = 3×10^{-3} L/s/m², average influent TOC of the synthetic wastewater = 4.2 mg/L, C = effluent TOC concentration, mg/L and C₀ = influent TOC concentration)
- Figure 7.16 Relationship between membrane correlation coefficient (MCC), filtration flux, and PAC dose (Average influent TOC of the biologically treated sewage effluent = 2.95 mg/L)
- Figure 7.17 Long-term performance of the submerged membrane hybrid system (Average influent TOC of the biologically treated sewage effluent = 3.0 mg/L, C = effluent TOC concentration, mg/L and C₀ = influent TOC concentration)
- Figure 7.18 Schematic diagram of the crossflow microfiltration hybrid system
- Figure 7.19 Effect of PAC dose on the permeate flux from the CFMF hybrid system (Membrane pore size = 0.11µm, TMP = 20 KPa, mixing intensity, G = 110.2 s⁻¹, mixing time = 6.6 min, initial TOC of the synthetic wastewater = 4.1 mg/L, initial turbidity = 0.75 NTU)
- Figure 7.20 Effect of PAC dose on the permeate flux from the CFMF hybrid system (Membrane pore size = 0.22µm, TMP = 20 KPa, mixing intensity, G = 110.2 s⁻¹, mixing time = 6.6 min, initial TOC of the synthetic wastewater = 4.1 mg/L, initial turbidity = 0.75 NTU)
- Figure 7.21 Effect of PAC dose and the TMP on the permeate flux from the CFMF hybrid system (Membrane pore size = 0.11µ m, PAC dose = 150 mg/L, mixing intensity, G = 110.2 s⁻¹, mixing time = 6.6 min, initial TOC of the synthetic wastewater = 4.1 mg/L, initial turbidity = 0.75 NTU)

- Figure 7.22 TOC profile of effluent from the CFMF hybrid system (Membrane pore size = $0.22\mu\text{ m}$, PAC dose = 150 mg/L , mixing intensity, $G = 110.2\text{ s}^{-1}$, mixing time = 6.6 min , $k_f = 6 \times 10^{-6}\text{ m/s}$, initial TOC of the synthetic wastewater = 4.1 mg/L , initial turbidity = 0.75 NTU , $C =$ effluent TOC concentration, mg/L and $C_0 =$ influent TOC concentration)
- Figure 7.23 Permeate volume with time and its prediction (Membrane pore size = $0.11\mu\text{ m}$, PAC dose = 150 mg/L , mixing intensity, $G = 110.2\text{ s}^{-1}$, mixing time = 6.6 min , TMP = 20 Kpa , $k_c = 8 \times 10^{-2}\text{ h/L}^2$, $k_s = 1 \times 10^{-1}\text{ L}^{-1}$, $J_0 = 2\text{ L/h}$)
- Figure 7.24 Permeate volume with time and its prediction (Membrane pore size = $0.22\ \mu\text{ m}$, PAC dose = 150 mg/L , mixing intensity, $G = 110.2\text{ s}^{-1}$, mixing time = 6.6 min , TMP = 20 Kpa , $k_c = 8 \times 10^{-5}\text{ h/L}^2$, $k_s = 4 \times 10^{-2}\text{ L}^{-1}$, $J_0 = 5\text{ L/h}$)
- Figure 7.25 Permeate volume with time and its prediction (Membrane pore size = $0.45\ \mu\text{ m}$, PAC dose = 150 mg/L , mixing intensity, $G = 110.2\text{ s}^{-1}$, mixing time = 6.6 min , TMP = 20 Kpa , $k_c = 6 \times 10^{-2}\text{ h/L}^2$, $k_s = 2 \times 10^{-1}\text{ L}^{-1}$, $J_0 = 5\text{ L/h}$)

EXTENDED ABSTRACT

Wastewater contains a matrix of organic and inorganic substances both in dissolved form and in suspension. Most of the biodegradable substances are removed in primary and secondary treatment processes. However, the conventional wastewater treatment processes cannot remove a number of synthetic and refractive organic substances. These substances can cause tremendous problem in the sewage treatment processes and in the water body where the effluent from the sewage plant is discharged. These substances produce odour, colour, and require a large quantity of disinfectant dose before the wastewater can be discharged into a water body. They can also significantly deplete the dissolved oxygen level of the water receiving body thus putting all the aquatic life in danger. The effluent from the sewage treatment plant therefore, needs to be passed through further treatment process, which is called advanced sewage treatment process. The advanced treatment processes consist of many treatment options. Depending upon the characteristics of the sewage and the level of treatment required, one has to select an appropriate treatment technology. Physico-chemical processes such as coagulation-flocculation and filtration, adsorption, and membrane application are some of the most viable treatment processes that can remove the organic substances to the desirable level. In this study, adsorption, biosorption or biofiltration, and adsorption-membrane hybrid systems were investigated for the removal of organics (in terms of total organic carbon (TOC)) from a low strength synthetic wastewater and a biologically treated secondary effluent from a sewage treatment plant, Sydney.

Adsorption experiments were conducted on low strength synthetic wastewater and the biologically treated sewage effluent using granular activated carbon (GAC) and powder activated carbon (PAC). The synthetic wastewater was prepared using three organic substances (glucose, peptone and yeast extract) and seven inorganic chemicals (MnSO_4 , CaCl_2 , NaHCO_3 , NaCl , $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, KH_2PO_4 , and $\text{NH}_2 \cdot \text{NH}_2 \cdot \text{H}_2\text{SO}_4$). The biologically treated sewage effluent was collected from the St. Marys sewage treatment plant, Sydney. Detailed experimental studies on adsorption equilibrium, batch kinetics and fixed bed were carried out, and the experimental results were predicted using suitable mathematical models.

The adsorption equilibrium was analysed with different initial organic concentration of the synthetic wastewater. The experimental results were then predicted using association theory (AT), characterization theory (CT), and the Freundlich isotherm. The experimental results showed unfavourable type of isotherm curve, and hence, the normal favourable isotherm equations such as Langmuir, Freundlich or Sippis isotherms were not very successful in describing the adsorption equilibrium results. The AT and the CT were better in predicting the adsorption equilibrium results than the commonly-used Freundlich isotherm. In this process, the adsorption equilibrium (isotherm) parameters were determined using a multivariable, non-linear regression, Nelder-Mead method by optimising an object function defined as the mean percent deviation between experimental and calculated equilibrium adsorption amounts. The isotherm parameters were found to be dependent on the initial organic concentration. Hence, it is important to estimate the isotherm parameters covering a wide range of organic concentration. Further, the adsorption equilibrium studies of the individual organic compounds indicated that the overall effects of the inorganic substances were unfavourable for the adsorption of organics in the wastewater. The organics of the synthetic wastewater were found to undergo biodegradation after 8 hours. Thus, the effect of the background substances in the wastewater, and the biodegradation effect are another important aspects that need to be considered while evaluating the effectiveness of the adsorption process for organic removal from the wastewater.

It is equally important to study the adsorption behaviour with time (i.e. adsorption kinetics). Adsorption kinetics of the organics in the wastewater was determined using linear driving force approximation (LDFA) model. Basically, the LDFA is a simplified expression of intraparticle diffusion of adsorbate into adsorbent particles. In this model, it is assumed that the uptake rate of adsorbate by an adsorbent particle is linearly proportional to the driving force developed due to the difference between the surface concentration and the average adsorbed phase concentration of the adsorbate. The main reason for using the LDFA method was the use of index (or lumped) parameter, total organic carbon (TOC), to express the total organic contents of the wastewater. The film mass transfer coefficient (k_f) was found to be dependent on the experimental conditions such as mixing intensity, the adsorbent dose and the initial organic concentrations. The film mass transfer coefficient (k_f) to the adsorbent increased when the mixing intensity

and the adsorbent dose were increased. However, the k_f value decreased with the increase in the initial organic concentration of the solution.

The adsorption isotherm parameters obtained from the association theory (AT) and the characterization theory (CT), were utilized to fit the experimental results using LDFA model. The isotherm parameters obtained from both the theories were found equally effective in predicting the experimental results. The overall effect of the dissolved inorganic compounds in the synthetic wastewater solution was observed to enhance the mass transfer rate to the GAC particle. The average value of the overall mass transfer rate was in the order of 10^{-6} m/s.

The application of adsorption system in practice is usually carried out in the fixed bed adsorption mode. The adsorbent (usually GAC) is packed in a column and the target pollutants are passed through either end to be adsorbed by the adsorbent. In this study, the fixed bed adsorption study was carried out in acrylic columns in the laboratory. The GAC bed depth, organic concentration of the feed solution, and the filtration velocity through the GAC bed were varied to evaluate the effectiveness of the fixed bed adsorption system. The experiments were carried out with both the biologically treated sewage effluent and the synthetic wastewater. The experimental results were predicted using the dynamic adsorption model. The film mass transfer coefficient (k_f) was obtained by fitting the fixed bed experimental data. The k_f increased when filtration rate was increased, but it decreased with the increase in the organic concentration of the feed solution. As expected, the value of k_f remained constant with the increase in GAC bed depth. The effect of axial dispersion coefficient was negligible, as the GAC bed depth and the size of the GAC particles used in this study were shallow and small respectively. The average value of the overall mass transfer rate in the fixed bed study was also in the order of 10^{-6} m/s but slightly less than that obtained in batch kinetics study.

The fixed bed system with attached microorganisms on the surface of the adsorbent (fixed bed medium) is referred to as a biofilter, where the organics are adsorbed (biosorption) and biodegraded by the microorganisms. The fixed bed adsorption experimentations were conducted for a longer duration to investigate the biological activity on the granular activated carbon (GAC). The experimental results showed the

growth of microorganisms on the surface of GAC particles. In other words, the adsorption system turned into biosorption or biofiltration system after few weeks of operation. The adsorption capacity of the GAC particles slowly exhausted with the growth of microorganisms with time. The overall organic removal efficiency of the system was however, not impaired by the growth of microorganisms. The organics were removed by the processes of biosorption and subsequent biodegradation. The biomass growth rate was found to fluctuate with time in sinusoidal pattern. Despite the fluctuation in the biomass, the TOC removal efficiency of the biofiltration system was consistent at 55 % for 77 days of continuous operation. Moreover, the daily backwashing provided at 30 % bed expansion to avoid filter clogging did not have adverse effect on the TOC removal efficiency of the biofilter. The organic removal efficiency of the biofilter changed when the filtration rate was altered from that in which the biofilter was acclimatized; however the organic removal pattern remained consistent with time. This result suggests that the biofilter should be operated in the same filtration velocity at which it is acclimatized to attain maximum efficiency of the filter.

A practical mathematical model was developed incorporating both adsorption and biodegradation of organics. The organic removal efficiency of the biofilter was successfully predicted using kinetics data obtained from the previous studies. The model was sensitive to the biofilm thickness and decay constant.

The adsorption-membrane hybrid system is emerging as a cost-effective membrane process for the organic removal. In this system, the organics are adsorbed on the adsorbent and the organic laden adsorbents are removed by the membrane separation process. In this study, the adsorption-membrane hybrid system was evaluated using submerged hollow fibre (pore size 0.1 μm), and the external loop crossflow microfiltration. Powdered activated carbon (PAC) was used to reduce the direct organic loading onto the membrane surface. The main function of membrane in these studies was to remove the organic laden PAC particles. The submerged PAC-Membrane hybrid system was found effective in removing dissolved organic substances both from the synthetic wastewater and the biologically treated effluent of a sewage treatment plant. The system has potential for its long-term application in the treatment of wastewater without the need of frequent membrane cleaning. This preliminary study

showed that the PAC-membrane hybrid system could be used for a long time effectively (over 47 days). At the initial stage of operation, the organic removal was mainly due to adsorption by PAC, but during the long-term application of the system, the adsorption capacity of the PAC was exhausted gradually, and the microbial communities developed on the PAC, in the suspension of the reactor, and on the membrane surface actively participated in the biodegradation of the organics.

An empirical mathematical model was developed for the submerged hollow fibre membrane hybrid system. The model predicted the organic removal efficiency of the system satisfactorily. A new term, membrane correlation coefficient (MCC) was introduced in the model to account for the adsorption of organics onto membrane surface. The MCC and the filtration rate (flux) were found to be the main model parameters that controlled the quality of the effluent from the system. Greater the value of MCC, better was the organic removal efficiency of the system. The MCC value was found to increase with the increase in the PAC dose to the system. Since only the short-term experiments were conducted in this study, the biological degradation of the organics was not included in the model. It is necessary to incorporate the biological degradation part in the model to predict the long-term efficiency of the system.

The external loop cross-flow microfiltration system with prior PAC addition was also tested using the synthetic wastewater. This study showed that the use of PAC helped not only in the organic removal but also in the enhancement of the filtration flux. The use of PAC was instrumental in increasing the operational life the membrane hybrid system by reducing the organic fouling on the membrane. The conventional pressure filtration models, cake filtration model (CFM) and standard blocking model (SBM) were used to successfully predict the experimental results. Since CFM was more effective in predicting the volume of the permeate flux from the hybrid system, one could infer that the fouling mechanism of the membrane was mainly due to the formation of cake layer on the membrane surface. However, the experimental conditions used in the hybrid system were not so favourable for removing the organics from the synthetic wastewater. The organic removal efficiency of the PAC-membrane hybrid system was only 25% for the PAC dose of 150 mg/L. The organic removal efficiency of the system depends mainly on the characteristics of the adsorbent and the influent wastewater solution, and the adsorbent dose.

This study shows that activated carbon can effectively be used in different operational modes and in different treatment processes to remove organics from the wastewater, and to produce effluent of high quality that can be reused for many purposes.