



UNIVERSITI PUTRA MALAYSIA

**NITRIFICATION AND DENITRIFICATION OF PARTIALLY TREATED
LANDFILL LEACHATE**

MANISYA ZAURI BINTI ABDUL WAHID.

FSMB 2004 11

**NITRIFICATION AND DENITRIFICATION OF PARTIALLY TREATED
LANDFILL LEACHATE**

By

MANISYA ZAURI BINTI ABDUL WAHID

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia in
Fulfilment of the Requirements for the Degree of Master of Science**

April 2004



Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

NITRIFICATION AND DENITRIFICATION OF PARTIALLY TREATED LANDFILL LEACHATE

By

MANISYA ZAURI BINTI ABDUL WAHID

April 2004

Chairman : Professor Mohd. Ali Hassan, Ph.D.

Faculty : Food Science and Biotechnology

In this study, biological removal of ammonia, nitrite and nitrate nitrogen of partially treated landfill leachate (PTLL) was conducted by nitrification and denitrification processes. The experiments were conducted by batch treatment using 16L stirred tank reactor in which 8 L of PTLL was treated with 0%, 1%, 5% and 10% (v/v) of centrifuged landfill leachate sludge and the pH was adjusted to 7 at every 12 hour interval. The treatment systems were kept above 80% saturated with oxygen (0.06-0.19 vvm).

It was found that the treatment with 10% centrifuged landfill leachate sludge was sufficient to reduce 93% and 63% of the PTLL's ammonia and nitrite, respectively, under aerobic condition. It was also observed that the level of nitrate can be reduced by 56% by biological means from the PTLL's original concentration of 13,500 ppm during nitrification process. However, subsequent denitrification was not possible due to foaming which occurred during the nitrification treatment with 10% centrifuged

landfill leachate sludge. Large loss of biomass from the system was experienced, even when the flowrate of air supplied was reduced to a very low level at 0.06 vvm. Furthermore, the impeller located at the upper part of the reactor's shaft was unable to break the large amount of foam formed.

As an alternative to prevent foaming, further experiments were carried out in a 6L reactor with the use of 4L synthetic media of (a) defined media with controlled pH between 7.5 and 8.5; (b) model leachate (without organic nitrogen) with (i) pH adjusted to 7 every 12 hours (ii) controlled pH between 7.5 and 8.5; and (c) model leachate (with organic nitrogen and pH controlled between 7.5 and 8.5. These media consisting of ammonia, nitrite and nitrate concentrations of 1000 ppm, 1500 ppm and 3000 ppm, respectively, were treated with 10% of centrifuged landfill leachate sludge for complete nitrification and denitrification processes and to isolate the microbes involved. The saturated oxygen was kept above 80% (0.02 vvm) throughout the treatments.

Complete nitrification and denitrification were achieved at 120 and 168 hours, when defined media and model leachate (without organic nitrogen) were used respectively, under controlled pH between 7.5 and 8.5. The cell population of both treatments was found to increase from 10^8 to 10^{10} cell/ml and 10^9 to 10^{10} cell/ml respectively, at the end of denitrification process, under C/N ratio of 0.4 in which acetic acid was used as carbon source.

Several strains were isolated from nitrification and denitrification processes. They were strains WNZ 1, WNZ 2 and WNZ 3 (ammonia oxidizers) which were unable to be identified by Biolog Identification System, *Acinetobacter calcoaceticus* and *Acidovorax konjaci* (nitrite oxidizers) and *Pseudomonas aeruginosa* 1, *Pseudomonas aeruginosa* 2 and *Pseudomonas aeruginosa* 3 (nitrate oxidizers).

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk Ijazah Master Sains

NITRIFIKASI DAN DINITRIFIKASI LELEHAN SISA PEPEJAL SEPARA RAWATAN

Oleh

MANISYA ZAURI BINTI ABDUL WAHID

April 2004

Pengerusi: Profesor Mohd. Ali Hassan, Ph.D.

Fakulti: Sains Makanan dan Bioteknologi

Kajian penyahan nitrogen amonia, nitrit dan nitrat nitrogen dari lelehan sisa pepejal separa rawatan secara biologi dilakukan melalui proses-proses nitrifikasi dan denitrifikasi. Eksperimen dilakukan secara rawatan 'batch' dengan menggunakan reaktor tangki pengadukan 16 L dimana lelehan sisa pepejal separa rawatan dirawat bersama 0%, 1%, 5% dan 10% (v/v) enapcemar lelehan sisa pepejal yang diempar dan pH di laraskan kepada 7 pada setiap 12 jam. Ketepuan oksigen di dalam system-sistem rawatan ini di kawal melebihi paras 80 % (0.06-0.19 vvm).

Didapati, rawatan bersama 10% enapcemar lelehan sisa pepejal yang diempar adalah memadai untuk menurunkan 93% dan 63% daripada kepekatan ammonia dan nitrit awalan lelehan sisa pepejal separa rawatan iaitu 400 dan 2000 ppm, setiap satunya di bawah keadaan arobik. Didapati juga bahawa paras nitrat dapat dikurangkan sebanyak 56% daripada kepekatan asal lelehan sisa pepejal separa rawatan iaitu 13,500 ppm pada proses nitrifikasi. Walaubagaimanapun, proses dinitrifikasi seterusnya tidak

dapat dijalankan kerana berlakunya pembuihan semasa rawatan bersama 10% enapcemar lelehan sisa pepejal yang diempar yang menyebabkan kehilangan banyak biomas di dalam system walaupun kepekatan oksigen yang dibekalkan telah diturunkan kepada 0.06 vvm. Pengaduk yang berada di bahagian atas bioreaktor tidak dapat memecahkan buih-buih yang terbentuk.

Sebagai alternatif, eksperimen selanjutnya dijalankan dengan penggunaan media sintetik seperti (1) media tetap dengan kawalan pH diantara 7.5- dan 8.5; (2) model lelehan sisa pepejal (tanpa nitrogen organik) dengan (i) pelarasan pH kepada 7 pada setiap 12 jam (ii) kawalan pH di antara 7.5 dan 8.5; dan (c) model lelehan sisa pepejal (dengan nitrogen organik) dengan kawalan pH di antara 7.5 dan 8.5. Media-media ini mengandungi kepekatan-kepekatan ammonia nitrit dan nitrat pada 1000 ppm, 1500 ppm dan 3000 ppm, setiap satunya dirawat bersama 10% enapcemar sisa pepejal yang diempar untuk pemerhatian proses-proses nitrifikasi dan dinitrifikasi yang lengkap dan untuk memencilkan mikrob-mikrob yang terlibat. Kepekatan oksigen dikekalkan melebihi paras 80% (0.02 vvm) sepanjang rawatan di jalankan.

Nitrifikasi dan dinitrifikasi yang dicapai adalah pada 120 dan 168 jam apabila media tetap dan media model lelehan sisa pepejal (tanpa nitrogen organik) digunakan, setiap satunya di bawah kawalan pH diantara 7.5 dan 8.5. Populasi sel untuk kedua-dua rawatan didapati meningkat dari 10^8 kepada 10^{10} sel/ml dan 10^9 kepada 10^{10} sel/ml, setiap satunya pada akhir proses denitrifikasi dengan nisbah C/N 0.4 dimana asid asetik digunakan sebagai punca karbon.

Beberapa strain dapat dipencilkan dari proses-proses nitrifikasi dan dinitrifikasi. Diantaranya ialah strain WNZ 1, WNZ 2 dan WNZ 3 (pengoksida-pengoksida ammonia) yang mana tidak dapat dikenalpasti oleh Sistem Pengenalpastian Biologi, *Acinetobacter calcoaceticus* dan *Acidovorax konjaci* (pengoksida-pengoksida nitrit) dan *Pseudomonas aeruginosa* 1, *Pseudomonas aeruginosa* 2 dan *Pseudomonas aeruginosa* 3 (pengoksida-pengoksida nitrat).

ACKNOWLEDGEMENTS

I wish to thank all postgraduate students and laboratory staff of Fermentation and Bioprocess Engineering, Department of Biotechnology for their assistance throughout the length of my research. I like to express my deepest gratitude towards my father, mother and also my two brothers for their love and support.

I would especially like to thank my supervisor Prof. Dr. Mohd. Ali Hassan and the supervisory committee, Prof. Dr. Mohamed Ismail Abdul Karim and Assoc. Prof. Dr. Arbakariya Ariff for their guidance, support and encouragement.

TABLE OF CONTENTS

	Page
ABSTRACT	ii
ABSTRAK	v
ACKNOWLEDGEMENTS	viii
APPROVAL	ix
DECLARATION	x
LIST OF TABLES	xvii
LIST OF FIGURES	xix
LIST OF ABBREVIATIONS	xxiv
 CHAPTER	
 I INTRODUCTION	 1
 II LITERATURE REVIEW	 3
Generation Process of Landfill Leachate	3
Current Treatment System of Landfill Leachate	5
Landfill Leachate Treatment in Malaysia	7
Foaming In Biological Wastewater Treatment	9
Composition and Characteristics of Landfill Leachate	12
Microbiology of Landfill Leachate	17
Landfill Leachate as Pollution	20
Forms of Nitrogen	21
Ammonia	21
Nitrite	23
Nitrate	24
Nitrogen Cycle	25
Nitrogen as Pollutant	26
Effect of Nitrogen Discharged	27
Nitrogen Removal Treatments	27
Biological Nitrogen Removal	28
Biological Nitrification and Denitrification	28
Bacterial Population of Nitrification	30
Nitrifying Bacteria	30
Ammonia Oxidizers	31
Nitrite Oxidizers	31
Nitrifiers and Their Characteristics	34
Ammonia Oxidizing Bacteria	34
Nitrite Oxidizing Bacteria	35
Biochemistry of Nitrification	36
Biochemical Pathway	36
Energy and Synthesis Relationship	40



Effect of Environmental Factors	42
Nitrification Inhibitors	43
Bacterial Population of Denitrification (Nitrate Oxidizers)	49
Biochemistry of Denitrification	50
Biochemical Pathway	50
Energy and Synthesis Relationship	52
Effect of Environmental Factors of Denitrification	54
C/N Relationship	54
Importance of Denitrification	60
Aerobic Denitrification	60
Nitrification and Denitrification of Landfill Leachate	62
Electron Microscopy (EM)	63
Scanning Electron Microscope (SEM)	64
Transmission Electron Microscope (TEM)	64
III GENERAL MATERIALS AND METHODS	66
Chemical Reagents	66
Landfill Leachate Treatment of AirHitam Sanitary Landfill	67
Partially Treated Landfill Leachate (PTLL) and Landfill Leachate Sludge	69
Experimental Design	70
Aerobic Batch Treatment of Partially Treated Landfill Leachate	71
Sludge Preparation	71
Dissolved Oxygen (D.O) Measurement	71
Reactor Setup	71
Aerobic Treatment of PTLL (Nitrification)	75
Nitrification and Denitrification of Defined Medium	75
Isolation of Ammonia Oxidizing Bacteria	77
Isolation of Nitrite Oxidizing Bacteria	78
Isolation of Nitrate Oxidizing Bacteria	78
Biolog MicroLog Identification System	79
Maintenance of Isolates	82
Medium	82
Maintenance and Growth Media	82
Preparation of Inoculum	82
Appropriate pH and Temperature of Isolates (Shake Flask System)	83
Microbial Growth Study	83
Ammonia, nitrite and nitrate removals	84
Analytical Methods	85
Quantitative Analyses	85
Ammoniacal Nitrogen Determination	85
Nitrite Nitrogen Determination	85
Nitrate Nitrogen Determination	86
Total Phosphate Determination	87
Acetic Acid Determination	87
Total Kjeldahl Nitrogen (TKN)	88
Chemical Oxygen Demand (COD)	89
Biological Oxygen Demand (BOD)	90
Total Solids (TS) and Suspended Solids (SS)	

	Measurements	92
	Volatile Suspended Solids (VSS)	93
	Optical Density (O.D)	93
	Cell Number	94
	Qualitative Analyses	95
	Cell Morphological Characteristics and Gram Staining	95
	Oxidase Test	96
	Catalase Test	96
	Mortality of Bacteria	96
	Cultural Characteristics	97
	Specimen Preparation for Electron Microscopy	97
	Scanning Electron Microscopy (SEM) and	
	Transmission Electron Microscopy (TEM)	97
	Negative Staining	99
IV	NITRIFICATION OF PARTIALLY TREATED LANDFILL	
	LEACHATE (PTLL)	100
	Introduction	100
	Material and Methods	102
	Landfill Leachate Sludge and Partially Treated Landfill Leachate	
	Effluent (PTLL)	102
	Characteristics of PTLL and Centrifuged Landfill	
	Leachate Sludge	102
	Batch Aerobic Treatment (Nitrification)	103
	Sample Analyses	104
	Results and Discussion	104
	Characteristics of Partially Treated Landfill	
	Leachate (PTLL)	104
	Characteristics of Landfill Leachate Sludge	107
	Batch Aerobic Treatment	108
	Nitrification of PTLL at Different Percentages of	
	Centrifuged Landfill leachate Sludge	108
	pH Status on Nitrification of PTLL	113
	TS, SS, VSS and Cell Concentration on	
	Nitrification of PTLL	114
	Phosphate Consumption During Nitrification of	
	PTLL	117
	BOD ₅ and COD Removal	117
	Conclusion	119
V	NITRIFICATION AND DENITRIFICATION OF MODEL	
	LEACHATE	120
	Introduction	120
	Materials and Methods	121
	Preparation of Defined Media for Nitrification and	
	Denitrification	121
	Preparation of Model Leachate (With Organic Nitrogen)	
	Media for Nitrification and Denitrification	122

Preparation of Model Leachate (Without Organic Nitrogen)	
Media for Nitrification and Denitrification	122
Sample Analyses	123
Results and Discussion	123
Nitrification and Denitrification of Defined Media	123
Nitrification of Model Leachate (With Organic Nitrogen)	
Media	130
Nitrification and Denitrification of Model Leachate	
(Without Organic Nitrogen) Media	136
Conclusion	137
VI ISOLATION, IDENTIFICATION AND CHARACTERIZATION OF NITRIFYING AND DENITRIFYING BACTERIA	138
Introduction	138
Materials and Methods	139
Preparation on the Isolation of Ammonia, Nitrite and Nitrate	
Oxidizers from Nitrifying and Denitrifying System	139
Sample Preparation for TEM and SEM of Isolated Nitrifiers	
and Denitrifiers	140
Preparation on Biochemical and Physical Characteristics of	
Isolated Nitrifiers and Denitrifiers	141
Biolog Identification of Isolated Nitrifiers and Denitrifiers	141
Results and Discussion	142
Bacterial Isolation of Ammonia, Nitrite and Nitrate Oxidizers	
from Nitrification and Denitrification System	142
Identification of Isolated Ammonia, Nitrite and Nitrate	
Oxidizers	142
Physical Characteristics of Isolated Ammonia, Nitrite and	
Nitrate Oxidizers	144
Conclusion	157
VII INFLUENCE OF CULTURE CONDITIONS ON THE GROWTH OF NITRIFYING AND DENITRIFYING BACTERIA	158
Introduction	158
Materials and Methods	161
Preparation for Appropriate pH and Temperature Test of Isolated	
Nitirfiers and Denitrifiers of Isolated Nitrifiers and Denitrifiers	161
Growth Study of Isolated Nitirfiers and Denitrifiers	161
Preparation for Different Ammonia, Nitrite and Nitrate	
Concentrations Test of Isolated Ammonia, Nitrite and	
Nitrate Oxidizers	163
Preparation for Different C/N Ratios Test of Isolated Nitrate	
Oxidizers	163
Samples Analyses	164
Results and Discussion	164
Effect of pH and Temperature on Isolated Nitrifiers and	
Denitrifiers	164
Growth Kinetic of Logistic Model on Isolated Nitrifiers	

	and Denitrifiers	169
	Preferable C/N Ratios of Isolated Nitrate Oxidizers	174
	Removal of Ammonia, Nitrite and Nitrate at Different Concentrations by Isolated Nitrifiers and Denitrifiers	178
Conclusion		188
VIII	SUMMARY, CONCLUSION AND SUGGESTIONS FOR FUTURE WORK	189
	Summary	189
	Suggestions	191
	Conclusion	191
	REFERENCES	193
	APPENDICES	213
	BIODATA OF THE AUTHOR	220

LIST OF TABLES

Table	Page
1 Number of landfill sites and levels in Malaysia (up to March 2002)	8
2 Characteristics of landfill leachate	15
3 The most frequently observed xenobiotic organic compounds (XOCs) in landfill leachate	16
4 Microbial isolates of landfill leachate	19
5 Common ammonia oxidizers	32
6 Common nitrite oxidizers	33
7 Characteristics of ammonia oxidizers	34
8 Characteristics of nitrite oxidizers	35
9a Inhibitory effect of organic and inorganic compounds	45
10(b-c) Inhibitory effect of organic and inorganic compounds	46
11 Ammonia nitrogen and nitrate nitrogen concentration range for <i>Nitrobacter</i> inhibition as function of pH at temperature 20 ⁰ C	47
12 Inorganic compounds that lead to inhibition of the nitrification process	47
13 Genera of bacteria which are abundant in sewage and capable of performing denitrification	49
14 Carbon sources in denitrifying experiments	58
15 Composition of indicator for TKN	89
16 Characteristics of raw and Partially Treated Landfill Leachate (PTLL) of AirHitam Sanitary Landfill, Puchong	106
17 Characteristics of landfill leachate sludge	107
18 Cell and phosphate concentrations in treatment of PTLL with different sludge percentages	116
19 BOD removal of model leachate	133
20 Cell numbers and phosphate concentrations in treatment of model	



	leachate (without organic nitrogen) with 10% centrifuged sludge	134
21	Isolated strains detected by Biolog Identification System	143
22	Physical characteristics of isolated strains	147
23	Cultural and biochemical characteristics of isolated strains	156
24	Summary on growth rates of isolated strains	171

LIST OF FIGURES

Figure		Page
1	Decomposition chain: from protein to nitrate	23
2	The Nitrogen Cycle with reference to nitrogen control in wastewater treatment	25
3	Microbial nitrogen cycle	38
4(a-b)	The electron transport of ammonia and nitrite oxidizers	39
5	The electron transport of nitrate oxidizers	51
6	Schematic diagram of landfill leachate treatment plant of AirHitam Sanitary Landfill, Puchong	68
7	Partially Treated Landfill leachate (PTLL) entering settling pond before been discharged to nearby river at treatment plant of Airhitam Sanitary Landfill, Puchong	69
8	Experimental design	70
9a	Reactor set up of Partially Treated Landfill Leachate (PTLL) treatment System	72
10b	Reactor set up of Partially Treated Landfill Leachate (PTLL) treatment System	73
11c	Reactor set up of Partially Treated Landfill Leachate (PTLL) treatment System	74
12	System set up of batch synthetic medium treatments	76
13a	Removals of ammonia, nitrite and nitrate in treatment of PTLL with 0% sludge	110
14b	Removals of ammonia, nitrite and nitrate in treatment of PTLL with 1% sludge	110
15c	Removals of ammonia, nitrite and nitrate in treatment of PTLL with 5% sludge	110
16d	Removals of ammonia, nitrite and nitrate in treatment of PTLL with 10% sludge	111
17	Profile of TKN removal with different percentages of sludge	112

18	pH profile during treatment of PTLL with different percentages of leachate sludge with pH adjusted to 7 at every 12 hours.	113
19	Total solids in treatment with different sludge percentages	115
20	Suspended solids in treatment with different sludge percentages	115
21	VSS in treatment with different sludge percentages	116
22	BOD removal of PTLL in treatment with different percentages of landfill leachate sludge	118
23	The COD removals during nitrification with different sizes of sludge	119
24	Nitrification and denitrification of defined media with 10% centrifuged landfill leachate sludge	125
25	Phosphate consumption and cell accumulation during nitrification and denitrification of defined media with 10% centrifuged landfill leachate sludge	126
26	Total solids and suspended solids of nitrification and denitrification of defined media	126
27	COD and VSS of the treatment of defined media	128
28 (a-c)	SEM micrograph of bacterial population at the end of ammonia, nitrite and nitrate removal	129
29	Ammonia removal of model leachate (without organic nitrogen) media treated with 10% centrifuged landfill leachate sludge	130
30a	Nitrite removal of model leachate(without organic nitrogen) media treated with 10% centrifuged landfill leachate sludge	132
31b	Nitrate removal of model leachate(without organic nitrogen) media treated with 10% centrifuged landfill leachate sludge	132
32	COD removal of model leachate(without organic nitrogen) media treated with 10% centrifuged landfill leachate sludge	133
33	Suspended solids of model leachate (without organic nitrogen) media treated with 10% centrifuged landfill leachate sludge	135
34	Total solids of model leachate (without organic nitrogen) media treated with 10% centrifuged landfill leachate sludge	135
35	VSS of model leachate treatment (without organic nitrogen) media	

	treated with 10% centrifuged landfill leachate sludge	136
36	Ammonia, nitrite and nitrate of Model leachate (with organic nitrogen) Media treated with 10% centrifuged landfill leachate sludge	137
37	Negative staining, SEM and TEM micrographs of isolated strain WNZ 1	148
38	Negative staining, SEM and TEM micrographs of isolated strain WNZ 2	149
39	Negative staining, SEM and TEM micrographs of isolated strain WNZ 3	150
40	Negative staining, SEM and TEM micrographs of isolated strain <i>A. calcoaceticus</i>	151
41	Negative staining, SEM and TEM micrographs of isolated strain <i>P. aeruginosa</i> 1	152
42	Negative staining, SEM and TEM micrographs of isolated strain <i>P. aeruginosa</i> 2	153
43	Negative staining, SEM and TEM micrographs of isolated strain <i>P. aeruginosa</i> 3	154
44	Effect of pH and temperature on growth of isolated strain WNZ 1	165
45	Effect of pH and temperature on growth of isolated strain WNZ 2	166
46	Effect of pH and temperature on growth of isolated strain WNZ 3	166
47	Effect of pH and temperature on growth of isolated strain <i>A. calcoaceticus</i>	167
48	Effect of pH and temperature on growth of isolated strain <i>P. aeruginosa</i> 1	167
49	Effect of pH and temperature on growth of isolated strain <i>P. aeruginosa</i> 2	168
50	Effect of pH and temperature on growth of isolated strain <i>P. aeruginosa</i> 3	168
51	Growth profile of isolated strain WNZ 1	169
52	Growth profile of isolated strain WNZ 2	170
53	Growth profile of isolated strain WNZ 3	170
54	Growth profile of isolated strain <i>A. calcoaceticus</i>	172

55	Growth profile of isolated strain <i>P. aeruginosa</i> 1	173
56	Growth profile of isolated strain <i>P. aeruginosa</i> 2	173
57	Growth profile of isolated strain <i>P. aeruginosa</i> 3	174
58a	Nitrate removal by <i>P. aeruginosa</i> 1 under different C/N ratios	175
59b	Nitrate removal by <i>P. aeruginosa</i> 2 under different C/N ratios	175
60c	Nitrate removal by <i>P. aeruginosa</i> 3 under different C/N ratios	176
61	Cell number, nitrate removal, phosphate and acetic acid consumption by <i>P. aeruginosa</i> 1 under C/N ratio of 0.4	178
62	Ammonia removal at initial ammonia concentration of 50 ppm by strain WNZ 1	180
63a	Nitrite removal at initial nitrite concentration of 375 ppm by <i>A. calcoaceticus</i>	181
64b	Nitrite removal at initial nitrite concentration of 750 ppm by <i>A. calcoaceticus</i>	182
65c	Nitrite removal at initial nitrite concentration of 1500 ppm by <i>A. calcoaceticus</i>	182
66d	Nitrite removal at initial nitrite concentration of 3000 ppm by <i>A. calcoaceticus</i>	182
67e	Nitrite removal at initial nitrite concentration of 6000 ppm by <i>A. calcoaceticus</i>	183
68f	Nitrite removal at initial nitrite concentration of 12,000 ppm by <i>A. calcoaceticus</i>	183
69	Nitrate removal by <i>A. calcoaceticus</i>	185
70a	Nitrate removal at initial nitrite concentration of 2000 ppm by <i>P. aeruginosa</i> 1	185
71b	Nitrate removal at initial nitrite concentration of 4000 ppm by <i>P. aeruginosa</i> 1	186
72c	Nitrate removal at initial nitrite concentration of 8000 ppm by <i>P. aeruginosa</i> 1	186
73d	Nitrate removal at initial nitrite concentration of 12,000 ppm by <i>P. aeruginosa</i> 1	187

74e Nitrate removal at initial nitrite concentration of 24,000 ppm by
P. aeruginosa 1

187



LIST OF ABBREVIATIONS

v/v	Volume per volume
C/N ratio	Carbon to nitrogen ratio of medium ppm
μ_{\max}	Maximum or initial specific growth rate (h^{-1})
BOD	Biological oxygen demand
COD	Chemical oxygen demand
rpm	Rotation per minute
TKN	Total kjedahl nitrogen
TS	Total solids
SS	Suspended solids
VSS	Volatile suspended solids
SBR	Sequencing batch reactor
ppm	Parts per million
mmol	Millimol
SEM	Scanning electron microscopy
TEM	Transmission electron microscopy
μm	Micrometer
O.D	Optical density
M	Molarity