UNIVERSITI PUTRA MALAYSIA

INFLUENCE OF pH AND INITIAL SLUDGE CONCENTRATION ON ANAEROBIC DIGESTION OF WASTE ACTIVATED SLUDGE

ONG KEAT KHIM

FK 2007 7

INFLUENCE OF pH AND INITIAL SLUDGE CONCENTRATION ON ANAEROBIC DIGESTION OF WASTE ACTIVATED SLUDGE

By

ONG KEAT KHIM

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the Degree of Doctor of Philosophy

January 2007

Specially dedicated to:

My beloved parent: Ong Ghee Chye and Han Suan Eng

and

My beloved husband: Teoh Chin Chuang

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

INFLUENCE OF pH AND INITIAL SLUDGE CONCENTRATION ON ANAEROBIC DIGESTION OF WASTE ACTIVATED SLUDGE

By

ONG KEAT KHIM

January 2007

Chairman: Associate Professor Fakhru'l-Razi Ahmadun, PhD

Faculty: Engineering

Although anaerobic digestion is a common process for treatment of sludge, the digestion rate remains low. Hydrolysis is the first step of anaerobic digestion process and generally is considered to be the rate-limiting step for the overall digestion process. Hence, improvement in the hydrolysis rate is needed to enhance anaerobic digestion of sludge. Chemical hydrolysis can be used as an alternative as it could improve the digestion performance of the sludge. However, hydrolysis process relies on enzymes excreted by the fermentative acidogens, and is strongly pH dependent. Consequently, determination of the optimum pH of sludge digestion is essential and required. In spite of pH, initial concentration of sludge is also an important factor that influences the anaerobic digestion performance of sludge. However, concentrations of total suspended solids (TSS) at a secondary clarifier and a thickener are 1.0% and 4.0% TSS, respectively.

This study focuses on a laboratory-scale research on improvement of anaerobic digestion of waste activated sludge (WAS) which was performed by chemical hydrolysis using 0.5 M H_2SO_4 and 4.0 M NaOH at temperature of 29 ± 1 °C and agitation of 150 rpm. The research was conducted in two phases: the first phase investigated the effect of pH at pH 6.00, 7.00, 8.00, 9.00 and uncontrolled pH on the digestion performance at initial concentration of 4.0% TSS; the second phase investigated and compared the performance of anaerobic digestion at initial concentrations of 1.0% and 4.0% TSS at the optimum pH which was determined from the first phase. Subsequently, determination of kinetic parameters and followed by developments of mathematical models and computer programs were performed at both phases**.**

Significantly higher average removals, removal rates and rate constants of TSS, volatile suspended solids (VSS), total chemical oxygen demand (TCOD) and particulate chemical oxygen demand (PCOD) at controlled pH compared to that at uncontrolled pH. The average removals and removal rates at uncontrolled pH could be improved by 1 to 4 times by controlled pH. Meanwhile rate constants could be improved by 1 to 7. The highest average removal, removal rate and rate constant were found at pH 6.00 followed by pH 8.00, 7.00, 9.00 and uncontrolled pH. The results also indicated that the optimum pH was at pH 6.00. The improvement of sludge digestion was attributed to the enhancement of sludge solubilisation by the chemical hydrolysis as higher soluble chemical oxygen demand (SCOD) concentration was observed at the controlled pH.

There was no significant difference in rate constant and removal of the sludge. However, significantly higher average removal rates of TSS, VSS, TCOD and PCOD were achieved at initial concentration of 4.0% TSS. The improvement of the average removal rates of TSS, VSS, TCOD and PCOD was 2.5 to 3.4 times over that at initial concentration of 1.0% TSS giving rise to a higher digestion performance at initial concentration of 4.0% TSS.

The experimental results fitted well in first-order models in both phases. High relationships between simulated and experimental results were obtained from both phases experiments with correlation coefficients (R^2) ranging from 0.80 to 0.99. Hence, the developed mathematical models can be considered as a useful tool for predicting the concentrations remaining and removals of TSS, VSS, TCOD and PCOD as well as digestion time.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai
memenuhi keperluan untuk ijazah Doktor Falsafah

PENGARUH pH DAN KEPEKATAN AWAL ENAPCEMAR KE ATAS PENCERNAAN ANAEROB SISA ENAPCEMAR TERAKTIF

Oleh

ONG KEAT KHIM

Januari 2007

Pengerusi: Profesor Madya Fakhru'l-Razi Ahmadun, PhD

Fakulti: Kejuruteraan

Pencernaan anaerob merupakan suatu proses yang lazim digunakan untuk rawatan enapcemar tetapi kadar pencernaan adalah rendah. Hidrolisis yang merupakan langkah pertama dalam proses pencernaan anaerob adalah langkah penentu kadar dalam proses keseluruhan. Maka peningkatan kadar hidrolisis adalah diperlukan untuk meningkatkan pencernaan anaerob enapcemar. Hidrolisis kimia boleh digunakan sebagai satu alternatif disebabkan ia mampu meningkatkan prestasi percernaan enapcemar. Namun begitu, proses hidrolisis bergantung kepada enzim yang dirembeskan oleh fermentasi asidogen dan sangat bergantung kepada pH. Justeru itu, penentuan pH optimum adalah penting dan diperlukan. Selain dari pH, kepekatan awal enapcemar juga merupakan satu faktor yang penting mempengaruhi prestasi pencernaan anaerob enapcemar. Namun, kepekatan jumlah pepejal terampai (TSS) pada tangki pemendapan dan tangki pemekatan masing-masing adalah 1.0% dan 4.0% TSS.

Kajian ini tertumpu kepada penyelidikan dalam peningkatan pencernaan sisa enapcemar teraktif oleh hidrolisis kimia dengan menggunakan 0.5 M H_2SO_4 dan 4.0 M NaOH pada suhu 29 ± 1 °C dan agitasi 150 rpm. Penyelidikan ini dijalankan dalam dua fasa: kajian kesan pH pada pH 6.00, 7.00, 8.00, 9.00 dan pH tanpa berkawal terhadap prestasi pencernaan pada kepekatan awal 4.0% TSS dalam fasa pertama; pada fasa kedua mengkaji dan membandingkan prestasi pencernaan anaerob pada kepekatan awal 1.0% dan 4.0% TSS pada pH optimum yang ditentukan dari fasa pertama. Seterusnya, penentuan parameter kinetik, diikuti pembangunan model matematik dan program komputer dijalankan pada kedua-dua fasa.

Purata pengurangan, purata kadar pengurangan dan purata pemalar kadar TSS, VSS, TCOD dan PCOD didapati lebih tinggi bererti pada pH terkawal. Purata pengurangan dan purata kadar pengurangan pada pH tanpa berkawal boleh ditingkatkan sebanyak 1 sehingga 4 kali ganda oleh pH terkawal. Manakala purata pemalar kadar dapat ditingkatkan sebanyak 1 sehingga 7 kali ganda. Maka prestasi pencernaan enapcemar pada pH terkawal adalah lebih baik daripada yang pH tanpa berkawal. Purata pengurangan, kadar pengurangan dan pemalar kadar yang tertinggi didapati pada pH 6.00 diikuti pH 8.00, 7.00., 9.00 dan pH tanpa berkawal. Keputusan ini juga menunjukkan pH optimum adalah didapati pada pH 6.00. Peningkatan dalam pencernaan enapcemar adalah disebabkan oleh peningkatan dalam keterlarutan enapcemar oleh hidrolisis kimia kerana kepekatan SCOD yang lebih tinggi diperolehi pada pH terkawal.

Tiada perbezaan yang bererti dalam purata pemalar kadar dan pengurangan enapcemar. Namun demikian, purata kadar pengurangan yang bererti dicapai pada kepekatan awal 4.0% TSS. Peningkatan purata kadar pengurangan TSS, VSS, TCOD dan PCOD adalah sebanyak 2.5 sehingga 3.4 kali ganda terhadap yang pada kepekatan awal 1.0% TSS, maka lebih tinggi prestasi pencernaan pada kepekatan awal 4.0% TSS.

Keputusan eksperimen pada kedua-dua fasa dapat memenuhi model tertib pertama dengan baik. Perhubungan yang tinggi di antara keputusan-keputusan simulasi dan eksperimen yang diperolehi daripada kedua-dua fasa kajian dengan pekali sekaitan (R^2) berjulat dari 0.80 sehingga 0.99. Maka model matematikal yang dibangunkan boleh dianggapkan sebagai satu alat yang berguna untuk meramalkan kepekatan yang tertinggal dan pengurangan TSS, VSS, TCOD dan PCOD begitu juga dengan masa pencernaan.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation and gratitude to my supervisor, Associate Professor Dr. Fakhru’l-Razi Ahmadun for his guidance, technical assistance, encouragement and support that has made this thesis possible.

I would like to extend my appreciation to Associate Professor Dr. Sa’ari Mustapha and Associate Professor Dr. Suraini Abdul Aziz for their kind cooperation and assistance throughout my study and also to the Ministry of Science, Technology and Environment of Malaysia for giving me financial support in the form of National Science Fellowship.

I would also like to thank the Department of Chemical and Environmental Engineering, Universiti Putra Malaysia and Indah Water Consortium, Malaysia for the research funding. Special thanks to Mr. Termizi Zakaria for his help in experimental work.

Finally, I wish to convey my special thanks to my husband and family members, who had supported me and contributed to the successful completion of this study.

I certify that an Examination Committee met on 26 January 2007 to conduct the final examination of Ong Keat Khim on her Doctor of Philosophy thesis entitled “Influence of pH and Initial Sludge Concentration on Anaerobic Digestion of Waste Activated Sludge” in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

Robiah Yunus, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Tey Beng Ti, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Norhafizah Abdullah, PhD
Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Mohamad Roji bin Sarmidi, PhD
Professor
Faculty of Chemical and Natural Resource Engineering
Universiti Teknologi Malaysia
(External Examiner)

Hasanah Mohd. Ghazali, PhD
Professor/Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 27 APRIL 2007

This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of Supervisory Committee are as follows:

Fakhru'l-Razi Ahmadun, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Sa'ari Mustapha, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Suraini Abd Aziz, PhD
Associate Professor
Faculty of Biotechnology and Biomolecular Sciences
Universiti Putra Malaysia
(Member)

AINI IDERIS, PhD
Professor/Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 10 MAY 2007

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

ONG KEAT KHIM

Date: 23 MARCH 2007

TABLE OF CONTENTS

	Page
DEDICATION	ii
ABSTRACT	iii
ABSTRAK	vi
ACKNOWLEDGEMENTS	ix
APPROVAL	x
DECLARATION	xii
LIST OF TABLES	xvi
LIST OF FIGURES	xx
LIST OF ABBREVIATIONS	xxiii

CHAPTER

1 INTRODUCTION 1.1
- 1.1 Problem Statements 1.2
- 1.2 Objectives of the Study 1.6
- 1.3 Scope of the Study 1.7

2 LITERATURE REVIEW 2.1
- 2.1 Domestic Wastewater 2.1
- 2.2 Domestic Wastewater Characteristics of Malaysia 2.2
- 2.3 Sludge 2.6
- 2.4 Anaerobic Digestion of Sludge 2.7
  - 2.4.1 Hydrolysis 2.10
  - 2.4.2 Fermentation (Acidogenesis) 2.12
  - 2.4.3 Methanogenesis 2.13
- 2.5 Advantages and Disadvantages of Anaerobic Digestion 2.14
- 2.6 Factors Controlling Anaerobic Digestion 2.15
  - 2.6.1 pH 2.15
  - 2.6.2 Sludge Concentration 2.16
  - 2.6.3 Temperature 2.18
  - 2.6.4 Retention Time 2.19
  - 2.6.5 Chemical Composition of Wastewater 2.19
  - 2.6.6 Toxicants 2.20
- 2.7 Wastewater Characteristics 2.21
  - 2.7.1 Chemical Oxygen Demand (COD) 2.23
  - 2.7.2 Volatile Suspended Solids (VSS) 2.24
  - 2.7.3 Total Suspended Solids (TSS) 2.24
- 2.8 Common Neutralisation Reagents 2.25
  - 2.8.1 Base Reagents 2.26
  - 2.8.2 Acid Reagents 2.29

2.9 Methods for Improving Sludge Digestion 2.29
    2.9.1 Chemical Pretreatment 2.30
    2.9.2 Thermal Pretreatment 2.32
    2.9.3 Thermo-chemical Pretreatment 2.33
    2.9.4 Mechanical Pretreatment 2.34
2.10 Kinetics of Anaerobic Digestion 2.36

3 METHODOLOGY 3.1
3.1 Anaerobic Digester System 3.1
3.2 Sludge Collection and Characterisation of Raw Waste Activated Sludge (WAS) Used 3.2
3.3 Anaerobic Digestions of Waste Activated Sludge (WAS) at Controlled and Uncontrolled pH 3.3
    3.3.1 Determination of Total Suspended Solids (TSS) and Volatile Suspended Solids (VSS) 3.4
    3.3.2 Determination of Total Chemical Oxygen Demand (TCOD) and Soluble Chemical Oxygen Demand (SCOD) 3.6
3.4 Anaerobic Digestions of Waste Activated Sludge (WAS) at Different Initial Concentrations 3.7

4 RESULTS AND DISCUSSION 4.1
4.1 Effect of pH on Anaerobic Digestion of Waste Activated Sludge (WAS) 4.1
    4.1.1 Average Initial Concentrations of Raw Waste Activated Sludge (WAS) Used at Controlled and Uncontrolled pH 4.1
    4.1.2 Variations in Average Concentrations with Digestion Time at Controlled and Uncontrolled pH 4.4
    4.1.3 Effect of pH on Average Removal 4.6
    4.1.4 Effect of pH on Average Removal Rate 4.13
    4.1.5 Effect of pH on Rate Constant and Development of Mathematical Models 4.18
    4.1.6 Analysis of Effect of pH on Average Removal, Removal Rate and Rate Constant 4.29
    4.1.7 Effect of pH on Soluble Chemical Oxygen Demand (SCOD) Production Profiles 4.35
    4.1.8 Comparison of Digestion Performance with Previous Studies 4.40
    4.1.9 Development of Computer Programs for Predictions of Removal, Concentration and Digestion Time at Controlled pH 4.45
    4.1.10 Validation of the Mathematical Models at Controlled pH 4.47

4.2 Anaerobic Digestions of Waste Activated Sludge (WAS) at Different Initial Concentrations 4.63
  4.2.1 Average Initial Concentrations of Raw Waste Activated Sludge (WAS) Used at Different Initial Concentrations 4.63
  4.2.2 Variations in Average Concentrations with Digestion Time at Different Initial Concentrations 4.65
  4.2.3 Average Removals at Different Initial Concentrations 4.67
  4.2.4 Average Removal Rates at Different Initial Concentrations 4.71
  4.2.5 Average Rate Constants and Development of Mathematical Models at Different Initial Concentrations 4.75
  4.2.6 Analysis of Averages Removal, Removal Rate and Rate Constant at Different Initial Concentrations 4.80
  4.2.7 Comparison of Soluble Chemical Oxygen Demand (SCOD) Production Profiles at Different Initial Concentrations 4.83
  4.2.8 Development of Computer Programs for Predictions of Removal, Concentration and Digestion Time at Initial Concentration of 1.0% TSS 4.84
  4.2.9 Validation of the Mathematical Models at Initial Concentration of 1.0% TSS 4.86

5 CONCLUSIONS AND RECOMMENDATIONS 5.1

REFERENCES R.1
APPENDICES A.1
BIODATA OF THE AUTHOR B.1

LIST OF TABLES

Table		Page
2.1	Domestic wastewater characteristics (Sewerage Services Department, 1998)	2.3
2.2	Total BOD load (kg/day) from sewage treatment plants of respective states of Malaysia (Malaysia Environmental Quality Report, 2004)	2.5
2.3	Common neutralising reagents	2.25
2.4	Summary of the methods of chemical, thermal, thermo-chemical and mechanical pretreatments in previous studies	2.35
4.1	Average initial concentrations of TSS, VSS, TCOD, SCOD and PCOD of raw WAS used at controlled pH and uncontrolled pH	4.2
4.2	The components of TCOD and TSS of raw WAS used at controlled pH	4.3
4.3	Average removals of TSS, VSS, TCOD and PCOD at controlled and uncontrolled pH	4.7
4.4	One-way ANOVA test of average removals of TSS at controlled and uncontrolled pH	4.9
4.5	Post Hoc Test of average removals of TSS at controlled and uncontrolled pH	4.9
4.6	One-way ANOVA test of average removals of VSS at controlled and uncontrolled pH	4.10
4.7	Post Hoc Test of average removals of VSS at controlled and uncontrolled pH	4.10
4.8	One-way ANOVA test of average removals of TCOD at controlled and uncontrolled pH	4.11
4.9	Post Hoc Test of average removals of TCOD at controlled and uncontrolled pH	4.11
4.10	One-way ANOVA test of average removals of PCOD at controlled and uncontrolled pH	4.12
4.11	Post Hoc Test of average removals of PCOD at controlled and uncontrolled pH	4.12

4.12 Average removal rates of TSS, VSS, TCOD and PCOD at controlled and uncontrolled pH 4.13

4.13 One-way ANOVA test of average removal rates of TSS at controlled and uncontrolled pH 4.14

4.14 Post Hoc Test of average removal rates of TSS at controlled and uncontrolled pH 4.14

4.15 One-way ANOVA test of average removal rates of VSS at controlled and uncontrolled pH 4.15

4.16 Post Hoc Test of average removal rates of VSS at controlled and uncontrolled pH 4.15

4.17 One-way ANOVA test of average removal rates of TCOD at controlled and uncontrolled pH 4.16

4.18 Post Hoc Test of average removal rates of TCOD at controlled and uncontrolled pH 4.16

4.19 One-way ANOVA test of average removal rates of PCOD at controlled and uncontrolled pH 4.17

4.20 Post Hoc Test of average removal rates of PCOD at controlled and uncontrolled pH 4.17

4.21 Average rate constants of k_{TSS}, k_e, k_{TCOD}, and k_h at controlled and uncontrolled pH 4.24

4.22 Mathematical models of TSS, VSS, TCOD and PCOD at controlled and uncontrolled pH 4.24

4.23 One-way ANOVA test of average k_{TSS} at controlled and uncontrolled pH 4.25

4.24 Post Hoc Test of average k_{TSS} at controlled and uncontrolled pH 4.25

4.25 One-way ANOVA test of average k_e at controlled pH and uncontrolled pH 4.26

4.26 Post Hoc Test of average k_e at controlled and uncontrolled pH 4.26

4.27 One-way ANOVA test of average k_{TCOD} at controlled and uncontrolled pH 4.27

4.28 Post Hoc Test of average k_{TCOD} at controlled and uncontrolled pH 4.27

4.29 One-way ANOVA test of average k_h at controlled and uncontrolled pH 4.28

4.30 Post Hoc Test of average k_h at controlled and uncontrolled pH 4.28

4.31 Improvement of average removals at controlled pH over that at uncontrolled pH 4.31

4.32 Improvement of average removal rates at controlled pH over that at uncontrolled pH 4.31

4.33 Improvement of average rate constants at controlled pH over that at uncontrolled pH 4.31

4.34 Comparison of average removals with previous studies 4.40

4.35 Comparison of average hydrolysis rate constants with previous studies 4.45

4.36 Correlation coefficients of simulated and measured concentrations at controlled pH 4.52

4.37 Correlation coefficients of simulated and measured removals at controlled pH 4.57

4.38 Correlation coefficients of simulated and measured digestion times at controlled pH 4.62

4.39 Average initial concentrations of TSS, VSS, TCOD, SCOD and PCOD of raw WAS used at different initial concentrations 4.64

4.40 The components of TCOD and TSS of raw WAS used at different initial concentrations 4.65

4.41 Average removals of TSS, VSS, TCOD and PCOD at initial concentrations of 1.0% and 4.0% TSS 4.67

4.42 Independent-Samples T test of average removals of TSS at initial concentrations of 1.0% and 4.0% TSS 4.69

4.43 Independent-Samples T test of average removals of VSS at initial concentrations of 1.0% and 4.0% TSS 4.70

4.44 Independent-Samples T test of average removals of TCOD at initial concentrations of 1.0% and 4.0% TSS 4.70

4.45 Independent-Samples T test of average removals of PCOD at initial concentrations of 1.0% and 4.0% TSS 4.71

4.46 Average removal rates of TSS, VSS, TCOD and PCOD at initial concentrations of 1.0% and 4.0% TSS 4.72

4.47 Independent-Samples T test of average removal rates of TSS at initial concentrations of 1.0% and 4.0% TSS 4.73

4.48 Independent-Samples T test of average removal rates of VSS at initial concentrations of 1.0% and 4.0% TSS 4.73

4.49 Independent-Samples T test of average removal rates of TCOD at initial concentrations of 1.0% and 4.0% TSS 4.74

4.50 Independent-Samples T test of average removal rates of PCOD at initial concentrations of 1.0% and 4.0% TSS 4.74

4.51 Average rate constants at initial concentrations of 1.0% and 4.0% TSS 4.75

4.52 Independent-Samples T test of average k_{TSS} at initial concentrations of 1.0% and 4.0% TSS 4.77

4.53 Independent-Samples T test of average k_e at initial concentrations of 1.0% and 4.0% TSS 4.78

4.54 Independent-Samples T test of average k_{TCOD} at initial concentrations of 1.0% and 4.0% TSS 4.78

4.55 Independent-Samples T test of average k_h at initial concentrations of 1.0% and 4.0% TSS 4.79

4.56 Mathematical models of TSS, VSS, TCOD, and PCOD at initial concentrations of 1.0% and 4.0% TSS 4.79

4.57 Improvement of average removal rates at initial concentration of 4.0% TSS over that at initial concentration of 1.0% TSS 4.82

4.58 Correlation coefficients between simulated and measured concentrations, between simulated and measured removals, and between simulated and measured digestion times at initial concentration of 1.0% TSS 4.90

LIST OF FIGURES

Figure		Page
1.1	Three-steps Model of Anaerobic Digestion	1.1
2.1	Composition of Sewage	2.1
2.2	Distribution of Sewage Treatment Plants by State of Malaysia, 2004 (Malaysia Environmental Quality Report, 2004)	2.4
2.3	Model for Anaerobic Digestion of WAS	2.8
2.4	Anaerobic Digestion Process	2.9
2.5	Fractionation of COD in Wastewater	2.22
2.6	Graphical Analysis for the Determination of Reaction Rate Constant, k, of First Order Reaction	2.43
3.1	Experimental Set-up of Anaerobic Digestion of WAS	3.1
4.1	Variations in Average Concentrations of (a) TSS with Digestion Time, (b) TCOD with Digestion Time, (c) PCOD with Digestion Time, (d) VSS with Digestion Time at pH 6.00, 7.00, 8.00, 9.00 and Uncontrolled pH	4.5
4.2	Variations in Average Removals of (a) TSS with Digestion Time, (b) TCOD with Digestion Time, (c) PCOD with Digestion Time, (d) VSS with Digestion Time at pH 6.00, 7.00, 8.00, 9.00 and Uncontrolled pH	4.8
4.3	Plots of ln C_t versus Time (t) at pH 6.00	4.19
4.4	Plots of ln C_t versus Time (t) at pH 7.00	4.20
4.5	Plots of ln C_t versus Time (t) at pH 8.00	4.21
4.6	Plots of ln C_t versus Time (t) at pH 9.00	4.22
4.7	Plots of ln C_t versus Time (t) at Uncontrolled pH	4.23
4.8	Relationship between Average Removal and pH	4.29
4.9	Relationship between Average Removal Rate and pH	4.29

4.10 Relationship between Average Rate Constant and pH 4.30

4.11 SCOD Production Profiles at Controlled and Uncontrolled pH 4.36

4.12 Predicted Concentrations Remaining and Removals of TSS, VSS, TCOD, and PCOD by the Developed Computer Program 4.46

4.13 Predicted Digestion Time by the Developed Computer Program at Controlled pH 4.47

4.14 Correlations between Simulated and Measured Concentrations of TSS, VSS, TCOD and PCOD at pH 6.00 4.48

4.15 Correlations between Simulated and Measured Concentrations of TSS, VSS, TCOD and PCOD at pH 7.00 4.49

4.16 Correlations between Simulated and Measured Concentrations of TSS, VSS, TCOD and PCOD at pH 8.00 4.50

4.17 Correlations between Simulated and Measured Concentrations of TSS, VSS, TCOD and PCOD at pH 9.00 4.51

4.18 Correlations between Simulated and Measured Removals of TSS, VSS, TCOD and PCOD at pH 6.00 4.53

4.19 Correlations between Simulated and Measured Removals of TSS, VSS, TCOD and PCOD at pH 7.00 4.54

4.20 Correlations between Simulated and Measured Removals of TSS, VSS, TCOD and PCOD at pH 8.00 4.55

4.21 Correlations between Simulated and Measured Removals of TSS, VSS, TCOD and PCOD at pH 9.00 4.56

4.22 Correlations between Simulated and Measured Digestion Times at pH 6.00 4.58

4.23 Correlations between Simulated and Measured Digestion Times at pH 7.00 4.59

4.24 Correlations between Simulated and Measured Digestion Times at pH 8.00 4.60

4.25 Correlations between Simulated and Measured Digestion Times at pH 9.00 4.61

4.26 Variations in Average Concentrations of TSS, VSS, TCOD and PCOD with Digestion Time at Initial Concentration of 1.0% TSS 4.66
4.27 Variations in Average Removals of TSS, VSS, TCOD and PCOD with Digestion Time at Initial Concentration of 1.0% TSS 4.68

4.28 Plots of ln C_t versus Time (t) at Initial Concentration of 1.0% TSS 4.76

4.29 Relationship between the Average Removal and Initial Concentration 4.80

4.30 Relationship between Average Removal Rate and Initial Concentration 4.80

4.31 Relationship between Average Rate Constant and Initial Concentration 4.81

4.32 SCOD Production Profiles at Different Initial Concentrations 4.83

4.33 Predicted Concentrations Remaining and Removals of TSS, VSS, TCOD and PCOD by the Developed Computer Program at Initial Concentration of 1.0% TSS 4.85

4.34 Predicted Digestion Time by the Developed Computer Program at Initial Concentration of 1.0% TSS 4.86

4.35 Correlations between Simulated and Measured Concentrations of TSS, VSS, TCOD and PCOD at Initial Concentration of 1.0% TSS 4.87

4.36 Correlations between Simulated and Measured Removals of TSS, VSS, TCOD and PCOD at Initial Concentration of 1.0% TSS 4.88

4.37 Correlations between Simulated and Measured Digestion Times at Initial Concentration of 1.0% TSS 4.89

LIST OF ABBREVIATIONS

BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
DOE	Department of Environment
HRT	Hydraulic retention time
PCOD	Particulate chemical oxygen demand
SCOD	Soluble chemical oxygen demand
TCOD	Total chemical oxygen demand
TOC	Total organic compound
TS	Total solids
TSS	Total suspended solids
VFA	Volatile fatty acid
VS	Volatile solids
VSS	Volatile suspended solids
WAS	Waste activated sludge
r_s	Rate of substrate removal
X_V	Concentration of volatile suspended solids (VSS)
k	Overall rate coefficient
K	Half velocity saturation constant
S	Concentration of substrate

r	Reaction rate
C	Concentration of substrate
k	Rate constant
C_t	Concentration of substrate at time t
C_0	Initial concentration of substrate
t	Time
k_{TSS}	Rate constant of TSS
C_{tTSS}	Concentration of TSS at time t
C_{oTSS}	Initial concentration of TSS
k_e	Decay rate constant
C_{tVSS}	Concentration of VSS (biomass) at time t
C_{oVSS}	Initial concentration of VSS
k_{TCOD}	Rate constant of TCOD
C_{tTCOD}	Concentration of TCOD at time t
C_{oTCOD}	Initial concentration of TCOD
k_h	Hydrolysis rate constant
C_{tPCOD}	Concentration of PCOD at time t
C_{oPCOD}	Initial concentration of PCOD