



UNIVERSITI PUTRA MALAYSIA

**STUDY OF CULTURE CONDITION FOR SOLID STATE
FERMENTATION OF SEWAGE TREATMENT PLANT SLUDGE TO
COMPOST**

NASSERELDEEN AHMED KABBASHI

FH 2002 13

**STUDY OF CULTURE CONDITION FOR SOLID STATE FERMENTATION OF
SEWAGE TREATMENT PLANT SLUDGE TO COMPOST**

By

NASSERELDEEN AHMED KABBASHI

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

April 2002

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

(ألم تر أن الله أنزل من السماء ماء فأخرجنا به ثمرات مختلفا ألوانها ومن الجبال جدد بيض وحمر
مختلف ألوانها وغرابيب سود * ومن الناس والدواب والأنعام مختلف ألوانه كذلك إنما يخشى الله
من عباده العلماء إن الله عزيز غفور)

(فاطر 27-28)

DEDICATION

This thesis is dedicated to my parents, soul of my brother Bukhari, and family, for all of the love, for their guidance, support, enthusiasm and encouragement that they have given me through my never ending education, without these none of this would have been even possible and in loving memory of my grandparents. To Son Musaab and my wife without her lifting me up when this thesis seemed interminable, I doubt it should ever have been completed.

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

STUDY OF CULTURE CONDITION FOR SOLID STATE FERMENTATION OF SEWAGE TREATMENT PLANT SLUDGE TO COMPOST

By

NASSERELDEEN AHMED KABBASHI

April 2002

Chairman : Associate Professor Fakhru'l-Razi Ahmadun, Ph.D.

Faculty : Engineering

With increasing global wastewater production, disposal of sewage sludge is always problematic. Landfilling sewage sludge is a feasible option and is currently practiced in many parts of the world, including Malaysia. Selangor is the fastest developing state in Malaysia with a population of about 4 million, attracting heavy foreign investments in industrial and trade sectors leading to a higher population flux during the last decade. Due to this industrial growth, considerable amounts of sewage sludge are generated and there is a considerable demand for landfilling. Hence, landfilling of sewage sludge is no more attractive and feasible.

Composting has become an established process adding value to a large and growing number of organic byproducts. Even so, composting systems and uses for compost are still evolving. Design, operation and control issues remain

key factors leading to the success or failure of the process. Environmental issues, product quality and utilization strategies have yet to be fully optimized for many applications to allow usage of the composting process on a sustainable and economic basis. Recent advances in the design, construction and operation of municipal, industrial and agricultural facilities have brought significant improvements to this field. New techniques for monitoring microbial diversity, specific pathogens and beneficial microorganisms have led to a better understanding of the composting process. It is now recognized that composting offers the potential to alleviate numerous environmental problems.

In this work, a medium scale horizontal drum bioreactor was designed and fabricated for composting sewage sludge. The sludge was collected from different treatment plants in Malaysia and amended with sawdust at different ratios (1:1, 1:1.5, 1:1.7, and 1:2), before composting. As a result, the initial C/N ratio, which is optimum for composting increased effectively from about 7.0 to around 18.0. Three different types of microorganisms namely *P.chrysosporium*, *Trichoderma harzianum*, and *Mucor hiemalis* isolated by the Biochemical Engineering laboratory, Putra University Malaysia, were used to inoculate the compost mixture to study their effects on the composting process.

To monitor the progress of composting during the experiments, parameters such as temperature, moisture content, C/N ratio, pH, electrical conductivity, and heavy metal content were measured. After composting and

curing of the compost, germination index, faecal coliform and *E. coli* of the compost were also determined.

This study showed that the sewage sludge can be composted in a horizontal drum bioreactor under controlled conditions. The profiles of various parameters monitored during composting showed trends similar to those reported in literature for composting of other organic wastes. Of the three organisms tested, the combination of *P.chrysosporium* and *Trichoderma harzianum* proved to be the most suitable for efficient composting of the sewage sludge.

The final C/N ratio of the compost in most experiments were found to be around 15.0, indicating the compost is fully matured and can be used safely for agricultural purpose. During composting, the heavy metal content also decreased below the acceptable limit. The pH decreased to 6.5. A slight increase in pH to 7.1 occurred as soon as the temperature of the compost increased to 49 °C. Electrical conductivity (EC) of composting material decreased from 1.83 dS/m to 1.67 dS/m, after a period, it increased gradually from 2.01 to 2.23 dS/m and remained at around 2.33 dS/m till the end of composting

The quality of the resulting compost was assured by the test for the germination index, which was around 80%. This qualified the compost to be

used to improve soil quality. Coliform test conducted assured that there is no pathogen in the composted material. The composted material also had low *E.coli* count. The experimental results show that the operational strategies followed for the bioconversion of sludge to compost in horizontal drum bioreactor, mixed with sawdust as the amendment, is successful and can be practiced in large scale.

From the experiments, the optimum operating condition for composting was the experiment T4 in which a mixture of sewage sludge treatment plant to sawdust was 1:1.7, and with a mixture of fungus *P.chrysosporium* and *Trichoderma harzianum*. The inoculum amount used was 2 mL for every 20 g of sludge and the spore count was 2.5×10^7 spore per mL. The optimum C/N ratio was 14.9, the temperature 49 °C maintained for three days, moisture content 40.2%, pH of 7.1, electrical conductivity of 2.33 dS/m, and the aeration rate was maintained at 0.6 L/min/kg.

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

**KAJIAN KEADAAN KULTUR UNTUK FERMENTASI FASA PEPEJAL SISA
ENAPCEMAR LOJI RAWATAN KEPADA KOMPOS**

Oleh

NASSERELDEEN AHMED KABBASHI

April 2002

Pengerusi : Profesor Madya Fakhru'l-Razi Ahmadun, Ph.D.

Fakulti : Kejuruteraan

Dengan pertambahan penghasilan airsisa global, pembuangan sisa enapcemar merupakan masalah yang sering berlaku. Tebusgunatanah sisa enapcemar merupakan langkah yang berkesan dan digunakan dengan meluas di kebanyakan tempat di dunia, termasuk Malaysia. Selangor adalah negeri yang paling cepat membangun di Malaysia dengan populasi penduduk menjangkau 4 juta, menarik banyak pelabur asing di dalam sektor industri dan perdagangan menjadikan populasi penduduknya akan bertambah dalam dekad terakhir ini. Kesan daripada pertumbuhan industri, dijangkakan sejumlah besar sisa enapcemar akan dijana dan permintaan untuk tanah juga akan bertambah. Oleh itu, tebusgunatanah untuk sisa enapcemar tidak lagi menjadi tarikan dan dipertimbangkan.

Pengkomposan merupakan proses terbaik untuk menambahkan nilai bagi pelbagai produk sampingan organik. Namun begitu, sistem pengkomposan dan kegunaan kompos masih dalam perancangan. Isu-isu rekabentuk, operasi dan

kawalan merupakan faktor utama kejayaan dan kegagalan proses ini. Isu-isu alam sekitar, kualiti produk dan strategi penggunaan masih tidak optima sepenuhnya bagi beberapa aplikasi untuk mendapatkan penggunaan proses pengkomposan pada kadar yang sesuai dan ekonomi. Kemajuan terkini dalam rekebentuk, pembinaan dan pengoperasian munisipal, kemudahan pertanian dan perindustrian telah memberikan peningkatan yang bernilai kepada bidang ini. Teknik-teknik baru dalam pengawasan pembiakan bakteria, spesifik patogen dan mikroorganisma berfaedah telah memberikan pemahaman yang lebih terhadap proses pengkomposan. Kini, proses pengkomposan telah diiktiraf berpotensi untuk mengurangkan pelbagai masalah alam sekitar.

Dalam kajian ini, bioreaktor dram mengufuk berskala sederhana telah direkabentuk dan dibina untuk pengkomposan sisa enapcemar. Sisa enapcemar diambil dari loji rawatan yang berbeza di seluruh Malaysia dan dicampurkan dengan habuk kayu pada nisbah yang berbeza (1:1, 1:1.5, 1:1.7 dan 1:2), sebelum pengkomposan. Keputusannya, nilai C/N awal, yang opsional untuk nisbah pengkomposan meningkat dari 7.0 kepada 18.0. Tiga jenis mikroorganisma yang berbeza yang dipencilkan oleh UPM iaitu *P. chrysosporium*, *Trichoderma harzium* dan *Mucor hiemalis*, digunakan sebagai inokulum bagi campuran kompos untuk mengkaji kesan mikroorganisma tersebut terhadap proses pengkomposan. Untuk mengawasi perjalanan proses pengkomposan, semasa eksperimen dijalankan, parameter seperti suhu, kandungan lembapan, nisbah C/N, pH, konduktiviti elektrik, dan kandungan

logam berat telah dikira. Selepas pengkomposan dan kawalan kompos, indeks pembenihan, *faecal coliform* dan *E. coli* bagi kompos juga dikira.

Eksperimen ini menunjukkan bahawa sisa enapcemar mudah dikomposkan menggunakan bioreaktor dram mengufuk di bawah keadaan kawalan. Profil bagi pelbagai parameter yang diawasi semasa pengkomposan menunjukkan bentuk yang sama seperti yang dilaporkan melalui literasi untuk pengkomposan sisa organik. Bagi ketiga-tiga organisma yang dikaji, kombinasi antara *P. chrysosporium* dan *Trichoderma harzianum* terbukti paling sesuai untuk pengkomposan sisa enapcemar yang efektif.

Nisbah C/N terakhir bagi kompos untuk setiap eksperimen diperolehi sekitar 15.0, menunjukkan bahawa kompos telah matang dan selamat digunakan untuk pertanian. Semasa pengkomposan, kandungan logam berat juga berkurangan daripada nilai yang dihadkan. Nilai pH telah berkurang kepada 6.5. Pertambahan pH yang ketara, 7.1 berlaku apabila suhu kompos meningkat kepada 49 °C. Konduktiviti elektrik (EC) bahan pengkomposan berkurang daripada 1.83 dS/m kepada 1.67 dS/m. Selepas satu ketika, ia telah meningkat secara berkala daripada 2.01 kepada 2.23 dS/m dan mencapai sekitar 2.33 dS/m sehingga proses selesai.

Kualiti bagi kompos dinilai menggunakan ujian indeks pembenihan kadar pertumbuhan, nilainya sekitar 80%. Kompos ini berkualiti digunakan untuk meningkatkan kualiti tanah. Ujian coliform dibuat telah memastikan bahawa

tiada patogen di dalam bahan yang dikompos. Bahan yang dikompos juga mempunyai bilangan *E. coli* yang rendah. Keputusan eksperimen menunjukkan strategi pengoperasian diikuti dengan biopenukaran enapcemar kepada kompos di dalam bioreaktor dram mengufuk, dicampurkan dengan habuk kayu sebagai bahan campuran, berjaya dan boleh dipraktikkkan di dalam skala yang lebih besar.

Daripada mengadakan percubaan bahawa keadaan yang terbaik adalah percubaan T4 dimana dicampuri dengan kekotoran dan sampah lumpur untuk mengubati tanaman kepada habuk adalah 1:1.7 dan dicampuri dengan cendawan atau kulat *P. chrysosporium* dan *Trichoderma harzianum*.

Kadar suntikan yang telah digunakan adalah 2mL untuk setiap 20 g dari Lumpur dan jumlah benih adalah 2.5×10^7 bagi tiap tiap mL. C/N yang terbaik dalam kadar 14.9 dan suhu adalah 49 °C menetapkan untuk tiga gari, kandungan kelembapan adalah 40.2%, pH 7.1, berkelakuan elektrik adalah 2.33 dS/m, dan kadar memperanginan adalah menetpkan sebanyak 0.6 L/min/kg.

ACKNOWLEDGEMENTS

In the Name of Allah, Most Gracious, Most Merciful. My endless thanks to Allah Azza Wejel. Peace and Blessings of God be upon all of us.

I would like to mention five people, who were helpful in my completion of this project my mother, my beloved wife, Associate Professor Dr. Fakhru'l-Razi, Professor Ramachandran, and Associate Professor Dr. Azni.

My mother always helped me by raising up her two hands to Allah Azza Wejel making Duaa and supporting me while I am abroad.

My wife Fatima A. Galal and Associate Professor Fakhru'l have been essential on the academic end of the production of this. My wife helped by encouraging me I thank her for listening to my countless complaints and soothing my worries when I was discouraged with this project. In addition, she also was a wonderful resource to rebound ideas off, and a fabulous proofreader. I would like to offer unceasing thanks to her, who was one of the few who kept encouraging me as I spent way too long finishing this thesis.

I especially want to thank Associate Professor Dr. Fakhru'l who was incredibly efficient which in turn led to his students having the opportunity to display the same level of efficiency in completing this project. He was supportive

and excellent in guiding us through this novel experience and his equally generous and wise guidance during its development.

Professor K.B Ramachandran was helpful, enthusiastic, and positive especially in the beginning and end stages of my thesis, for the technical discussions, help with experimental setup and general advice I have learned various things, from him, such as the way of thinking, and the way of proceeding with research.

In particular I would like to acknowledge the help of Associate Professor Dr. Azni for his support, who always helped by good supervisions and with generosity of new ideas.

Thank you!!

I am grateful to all my friends from the Department of Chemical and Environmental Engineering, Universiti Putra Malaysia, for being the surrogate family during the many years I stayed there and for their continued moral support there after, Zahangir, Abul, Ibrahim, Isam, and Hassan. Puan Hashima (Soil Department, UPM), who was eager and helpful for the tests of all experimental works, I wish her good luck. All technicians in the lab are especially thanked for their care and attention.

Finally, I am forever indebted to my parents, my great father Ahmed Kabbashi, who was always running after our education, and my gratefulness

also expands to my eldest brother Ismail, sisters Ikhlas and Zizi for their understanding, endless patience and encouragement when it was most required. I am also grateful to Mohamed Bukhari and Mohamed Ismail for their moral support there after.

My great thanks to IWK, who supported this project financially. Last, but certainly not least, I would like to thank my wife, dear Son Musaab, who are my supports through everything!

I certify that an Examination Committee met on 17th April 2002 to conduct the final examination of Graduate Student on his Doctor Philosophy thesis entitled "Study of Culture Condition for Solid State Fermentation of Sewage Treatment Plant Sludge to Compost" 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:

Sa'ari Mustapha, Ph.D.
Associate Professor,
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Fakhru'l-Razi Ahmadun, Ph.D.
Associate Professor,
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Azni Idris, Ph.D.
Associate Professor,
Faculty of Engineering
Universiti Putra Malaysia
(Member)

K.B. Ramachandran, Ph.D.
Professor,
Faculty of Engineering
Universiti Malaya
(Member)



SHAMSHER MOHAMAD RAMADILI, Ph.D.
Professor / Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 15 MAY 2002

The thesis submitted to the Senate of Universiti Putra Malaysia has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy.

Aini Ideris, Ph.D.
Professor / Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

DECLARATION

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



Nassereldeen Ahmed Kabbashi

Date: 14/05/2002

TABLE OF CONTENTS

		Page
DEDICATION		ii
ABSTRACT		iii
ABSTRAK		vii
ACKNOWLEDGEMENTS		xi
DECLARATION FORM		xvi
LIST OF TABLES		xxi
LIST OF FIGURES		xxiii
LIST OF ABBREVIATIONS		xxv
CHAPTER		
1	INTRODUCTION	1
	1.1 The problem of Sewage Sludge	1
	1.2 Composting Defined	5
	1.3 Drum Bioreactor	6
	1.4 Statement of the Research Problem	7
	1.5 Objectives	8
2	LITERATURE REVIEW	9
	2.1 Formation of Sewage Sludge	9
	2.2 Physical and Chemical Properties of Sludge	12
	2.3 Problem of Sludge	17
	2.4 Sewage Sludge in Malaysia	19
	2.4.1 Management of Sludge in Malaysia	23
	2.4.2 Treatment Technologies	27
	2.4.2.1 Mechanical Plant	28
	2.4.2.2 Communal Septic Tank	29
	2.4.2.3 Imhoff Tanks	29
	2.4.2.4 Oxidation Bonds	30
	2.5 Ultimate Disposal of Sludge and Utilization	32
	2.6 Bulking Agent	35
	2.7 Composting Process	39
	2.7.1 Dewatering	42
	2.7.2 Mixing	44
	2.8 Composting	44
	2.8.1 Historical Background of Composting	47
	2.8.2 Biochemistry of Composting	50
	2.8.3 Types of Composting	52
	2.8.4 Advantages of Composting	55
	2.8.5 Composting Techniques	57

	2.8.5.1	Windrow Composting	.....	57
	2.8.5.2	Aerated Pile Composting	.....	58
	2.8.5.3	Mechanical Composting	.....	59
	2.8.5.4	Other Types of Composting		59
	2.8.6	The Phases of Composting	.....	60
	2.8.7	Composting and Bioreactors	.....	61
2.9		Environmental Factors	.....	62
	2.9.1	Compost Chemistry	.....	63
	2.9.1.1	C/N Ratio	.....	63
	2.9.1.2	Nitrogen Activator	.....	68
	2.9.1.3	Carbon Source	.....	69
	2.9.1.4	Oxygen Supply	.....	70
	2.9.1.5	Nutrient Balance	.....	71
	2.9.1.6	Hydrogen Ion Level (pH)	.....	72
	2.9.1.7	Chemical Additives	.....	76
	2.9.2	Compost Physics	.....	76
	2.9.2.1	Temperature Curve	.....	77
	2.9.2.2	Mechanisms of Heat Loss	.....	82
	2.9.2.3	Particle Size	.....	83
	2.9.2.4	Aeration	.....	87
	2.9.2.5	Moisture Content	.....	91
	2.9.2.6	Agitation	.....	93
	2.9.2.7	Additives	.....	94
2.10		Compost Microorganisms	.....	94
	2.10.1	Bacteria	.....	95
	2.10.2	Fungi	.....	97
	2.10.3	Protozoa	.....	103
	2.10.4	Actinomycetes	.....	103
	2.10.5	Rotifers	.....	104
2.11		Pathogens	.....	104
	2.11.1	Pathogen Reduction	.....	106
	2.11.2	Pathogen Risks	.....	107
2.12		Use of Indicator Organisms	.....	108
2.13		Monitoring the Process	.....	110
	2.13.1	Temperature Rise and Fall	.....	111
	2.13.2	Aesthetics Changes	.....	113
	2.13.3	Molecular (Chemical) Changes	.....	113
2.14		Compost Maturity	.....	115
2.15		Compost Curing	.....	117
2.16		Screening	.....	118
2.17		Solid State Fermentation (SSF)	.....	119
	2.17.1	Examples of SSF Process	.....	123
	2.17.2	Factors Influencing SSF Process Efficient		126
	2.17.3	Bioreactors of SSF	.....	127
	2.17.3.1	Vertical Bioreactor	.....	130
	2.17.3.2	Horizontal Bioreactor	.....	132
	2.17.3.3	Rotating Drum Bioreactor	.....	133

	2.17.3.4	Cylindrical Reactor	135
	2.17.3.5	Agitated Bed Reactors	137
	2.17.3.6	Trench Bioreactor	137
	2.17.3.7	Other Types of Bioreactors	137
3	MATERIALS AND METHODS		138
	3.1	Materials	138
	3.2	Chemical Reagents	138
	3.3	Sewage Sludge Cake (SSC)	139
	3.4	Horizontal Sludge Bioreactor Compost	140
	3.4.1	Horizontal Sludge Bioreactor Description.....	141
	3.5	Solid State Fermentation Techniques	142
	3.5.1	Steps of Solid State Fermentation Techniques	144
	3.6	Microorganisms and its Maintenance	144
	3.6.1	Preparation of Inoculum & Media Composition	145
	3.6.1.1	<i>Mucor hiemalis</i>	146
	3.6.1.2	<i>Trichoderma harzianum</i>	147
	3.6.1.3	<i>P.henarochaerate Cryosporium</i>	147
	3.7	Cellulolytic Cultures as Inoculant in Composting.....	147
	3.8	Analysis of Compost	148
	3.8.1	Physical Analysis	148
	3.8.1.1	Determination of structure, texture, colour and odour.....	148
	3.8.1.2	Determination of Moisture Content.....	148
	3.8.1.3	Determination of Temperature	148
	3.8.2	Chemical Analysis	150
	3.8.2.1	Hydrogen Ion Activity (pH) and EC.....	150
	3.8.2.2	Organic Carbon Content	151
	3.8.2.3	Determination of Nitrogen Content.....	151
	3.8.2.4	Aqua Regia Extraction Methods for Determination of Trace Elements (Cd, Cu, Zn (Pb, Cr, Ca, Mg, and K)	151
	3.8.2.5	Phosphorous Content	152
	3.8.2.6	Biological Analysis (Germination Test)	152
	3.8.3	Evaluation of the Microbiological Parameters...	153
	3.9	Data Analysis	153
4	RESULTS AND DISCUSSIONS		154
	4.1	Sludge Characterization	154
	4.2	Composition Studies	156
	4.3	Composting Methods	156
	4.4	Typical Composting Experiment	159
	4.5	Composting Experiments	168
	4.6	Physical Observation	168
	4.7	Studies on the Progress of Composting	169

4.7.1	Temperature Profile	172
4.7.2	Changes in Moisture Content	176
4.7.3	Changes of pH and Conductivity	178
4.7.3	Changes in C, N and C/N Ratio	186
4.8	Effect of Composting on Heavy Metals	195
4.9	Curing	205
4.10	Evaluation of Toxicity of Composts	207
4.10.1	Faecal Coliform	208
4.10.2	Escheridia Coli	210
4.11	Mass Balance of Composting	211
5	CONCLUSIONS AND RECOMMENDATIONS	214
	REFERENCES	219
	APPENDIX	
A	Common Analytical Method	235
A1	Determination of Moisture Content	235
A2	Determination of Total Volatile Solids	237
A3	Determination of Total Kjeldahl Nitrogen (Total Nitrogen) Determination by Micro-Kjeldahl Method	239
A4	Aqua Regia Extraction Method for Determination of Trace Elements (Cd, Fe, Cu, Zn, Pb, Cr, Ca, Mg, Mn, and K).....	240
A5	Determination of Phosphorous by Ash Method	241
B1	Evaluation of the Microbiological Parameters	242
	BIODATA OF THE AUTHOR	243

LIST OF TABLES

Table	Page
1.1 Typical composition of untreated domestic sewage.....	2
2.1: Characteristics of the effluents to be discharged on land.....	10
2.2: Composition of organic matter.....	51
2.3: Approximate composition of materials suitable for composting	64
2.4: category of microorganisms.....	102
2.5: Major pathogens found in Sewage and disease associated with these pathogens.....	105
2.6: Lethal temperature time conditions from some common pathogen and parasites.....	108
2.7: Comparison between liquid and solid substrate fermentations	125
2.8: Main application of SSF process in various economical sectors	126
4.1: Characteristics of sewage sludge, sawdust and soil.....	155
4.2: Experiments composition studies	157
4.3: Materials added to get an optimal C/N for the input sludge ...	158
4.4: Change in parameter Value	164
4.5: Changes in temperature during composting (°C)	174
4.6: Changes in moisture contents during composting (%)	177
4.7: Changes in pH during composting	180
4.8: Changes in EC during composting (dS/m)	183
4.9: Zero order rates constant estimated by linear regression	188
4.10: Changes in total carbon during composting (%)	189

4.11: Changes in total nitrogen during composting (%)	189
4.12: Changes in C/N ratio during composting	193
4.13: Heavy metals content (g/kg) in compost, from HDB experiments....	197
4.14: Changes in cress seed germination index (%)	207
4.15: Evolution during the composting process	211
4.16: Mass balance of composting processes	213

LIST OF FIGURES

Figure	Page
2.1: What Enters the Sewerage System from Household	21
2.2: Mechanical Dewatering at IWK Plant	29
2.3: The Composting Process	41
2.4: Soil Sterilization Temperature	106
2.5: Interactions on a Solid State Fermenter	127
2.6: Vertical Bioreactor	132
2.7: Horizontal Bioreactor	133
2.8: Rotating Drum	135
2.9: Cylindrical Reactor	136
3.1: Flow Diagram of the HDB Composting	141
3.2: Schematic Diagram of a Horizontal PVC rotating HDB	143
4.1: Stages of Solids Processing Operation	162
4.2: Horizontal Drum Bioreactor (HDB)	163
4.3: Changes in C, N & C/N ratio changes during Composting.....	167
4.4: Changes in pH and EC during Composting	170
4.5: Organic Carbon Variation during Composting	171
4.6: Temperature Variation during Composting	175
4.7: Moisture Content Variation during Composting	179
4.8: pH Variation during Composting	184
4.9: EC Variation during Composting	185
4.10 Plot % carbon remaining against days for various experiments	190
4.11: Nitrogen (%) Variation during Composting	191

4.12: C/N Ratio Variation during Composting	194
4.13: Changes in Cd during the Composting Process	198
4.14: Changes in Fe during the Composting Process	199
4.15: Changes in Cu during the Composting Process	200
4.16: Changes in Zn during the Composting Process	201
4.17: Changes in Cr during the Composting Process	202
4.18: Changes in Pb during the Composting Process	203
4.19: Changes in Ca during the Composting Process	204
4.20: A Schematic Description of the Drum Composter System.....	206
4.21: Sewage Sludge Compost after Curing	206
4.22: Changes in Cress Seed Germination Index (%)	209
4.23: Mass Balance for Compost Systems	212