



Cairo University

**BIOSORPTION OF DIFFERENT HEAVY METALS FROM
WASTEWATER USING NEW FUNGI WASTE
MATERIAL**

BY

SALMAN HUSSEIN ABBAS

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

In
Chemical Engineering

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2015

**BIOSORPTION OF DIFFERENT HEAVY METALS FROM
WASTEWATER USING NEW FUNGI WASTE
MATERIAL**

BY

SALMAN HUSSEIN ABBAS

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

In
Chemical Engineering

Under the supervision of

Prof. Dr. Tarek M. Moustafa

Prof. Dr. Ibrahim M. Ismail

Professor of Chemical Engineering
Chemical Engineering Department
Faculty of Engineering, Cairo University

Professor of Chemical Engineering
Chemical Engineering Department
Faculty of Engineering, Cairo University

Prof. Dr. Abbas H. Sulaymon

Professor of Chemical Engineering
Chemical Engineering Department
College of Engineering, Baghdad University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2015

**BIOSORPTION OF DIFFERENT HEAVY METALS FROM
WASTEWATER USING NEW FUNGI WASTE
MATERIAL**

BY

SALMAN HUSSEIN ABBAS

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY
In
Chemical Engineering

Approved by the
Examining Committee

Prof. Dr. Tareq Mohammad Moustafa, Thesis Main Advisor

Prof. Dr. Ibrahim Mohammad Ismail, Member

Prof. Dr. Nagwa Mahmoud El-Mansy, Internal Examiner

Prof. Dr. Nabil Abdel Basset Ibrahim, External Examiner
National Research Centre

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2015

ACKNOWLEDGMENTS

First of all I must submit gratefully thanks to the mighty God that able me with a support of many cooperative people to end this research.

By ending of this research I must keep in mind some persons who without their cooperation, dedication and commitment this research may not see the light.

I would like to express my sincere thanks and deep gratitude to my supervisors **Prof. Dr. Tarek M. Moustafa, Prof. Dr. Ibrahim M. Ismail and Prof. Dr. Abbas H. Sulaymon** for their a valuable guidance, constant support, understanding throughout the present work, kindness, encouragement , suggestions and utmost effort and interest through the work that contributed in its completeness.

I wish to express my deepest respect and sincere appreciation to the head of the chemical engineering department, faculty of engineering, Cairo university **Prof. Dr. Fatma H. Ashour** and head of the chemical engineering department, college of engineering, Baghdad university, **Assist. Prof. Dr. Basma A. Abid and Assist. Prof. Dr. Hassan F. Makki** for their support and encouragement throughout this work.

Finally, I wish to express my deepest respect and sincere appreciation to my family, for their encouragement throughout this work, and to all who helped me.

Salman

Dedication

Dedicated to

- *The memory of my father*
- *The big heart, my mother*
- *My wife, shatha*
- *My daughters, Ouras, hajer,
Taftaf and my honey Naba*
- *All my brothers and sisters*

Salman

Table of Contents

ACKNOLEDGEMENT.....	I
DEDICATION.....	II
TABLE OF CONTENTS.....	III
LIST OF TABLES.....	IV
LIST OF FIGURES.....	V
NOMENCLATURE.....	VI
ABSTRACT.....	VII
CHAPTER 1: INTRODUCTION.....	1
1.1 BACKGROUND.....	1
1.2 HEAVY METALS.....	1
1.2.1 HARMFAL EFFECT OF HEAVY METALS.....	2
1.2.1.1 COPPER.....	2
1.2.1.2 COBALT.....	2
1.2.1.3 LEAD.....	3
1.2.1.4 CADMIUM.....	3
1.3 CONVENTIONAL REMOVAL METHODS.....	4
1.3.1. ADSORPTION PROCESS.....	4
1.3.2. BIOSORPTION PROCESS.....	4
1.3.2.1 FUNGAL DEAD BIOMASS.....	5
1.4 PROBLEM STATEMENT.....	6
1.5 OBJECTIVE OF THE STUDY.....	6
1.6 MAIN ACTIVITY AND METHODOLOGIES.....	7
CHAPTER 2: LITERATURE SURVEY.....	8
2.1 INTRODUCTION.....	8
2.2 ADSORPTION PHENOMENA.....	9
2.3 TYPES OF ADSORPTION.....	10
2.3.1 PHYSICAL ADSORPTION.....	10
2.3.2. CHEMICAL ADSORPTION.....	11
2.3.3. EXCHANGE ADSORPTION	11
2.4 FUNDAMENTAL OF ADSORPTION.....	12
2.5 MECHANISMS OF ADSORPTION.....	12
2.6 ADSORBENT.....	13
2.6.1 PHYSICAL PROPERTIES OF THE ADSORBENT.....	13

2.6.1.1. ADSORPTION PORES.....	13
2.6.1.2. ADSORBENT SPECIFIC SURFACE AREA.....	14
2.7 ACTIVATED CARBON.....	14
2.7.1. PREPARATION OF ACTIVATED CARBON.....	15
2.7.1.1. PHYSICAL ACTIVATION.....	15
2.7.1.2 CHEMICAL ACTIVATION.....	15
2.8 BIOSORPTION.....	16
2.8.1. ADVANTAGES OF BIOSORPTION PROCESS.....	16
2.9 BIOSORBENTS.....	17
2.9.1. TYPES OF BIOSORBENTS.....	19
2.9.1.1. BACTERIA.....	19
2.9.1.2 ALGAE.....	20
2.9.1.3. FUNGI AND YEAST.....	22
2.9.1.4 WASTE OF ACTIVATED SLUDGE.....	24
2.9.2. MECHANISMS OF BIOSORPTION PROCESS.....	24
2.9.2.1. PHYSICAL ADSORPTION PROCESS BY BIOMASS.....	27
2.9.2.2. ION-EXCHANGE BY BIOMASS.....	27
2.9.2.3. COMPLEXATION BY BIOASS.....	28
2.9.2.4. PRECIPITATION BY BIOASS.....	28
2.9.2.5. TRANSPORT ACROSS THE CELL MEMBRANE.....	28
2.9.3. FACTORS AFFECTING BIOSORPTION OF METALS.....	29
2.9.3.1 TEMPERATURE.....	29
2.9.3.2 TYPES OF BIOMASS.....	29
2.9.3.3 THE SURFACE AREA TO VOLUME.....	29
2.9.3.4 ACIDITY.....	29
2.9.3.5 BIOMASS DOSAGE.....	30
2.9.3.6 INITIAL METAL ION CONCENTRATION.....	30
2.9.3.7 METAL AFFINITY TO THE BIOSORBENT.....	31
2.9.3.8 EFFECT OF AGITATION SPEED.....	31
2.9.3.9 EFFECT OF CONTACT TIME.....	31
2.9.3.10 EFFECT OF PARTICLE SIZE.....	31
2.10 ADSORPTION/BIOSORPTION SYSTEMS.....	32
2.10.1 BATCH ADSORPTION / BIOSORPTION SYSTEM.....	32
2.10.2 FIXED-BED ADSORPTION / BIOSORPTION SYSTEM.....	33
2.11 ADSORPTION / BIOSORPTION SYSTEMS.....	34

2.12	ADSORPTION / BIOSORPTION MODELS.....	35
2.12.1	SINGLE COMPONENT ISOTHERM MODELS.....	35
2.12.1.1	FREUNDLICH MODEL.....	35
2.12.1.2	LANGMUIR MODEL.....	36
2.12.1.3	TEMKIN MODEL.....	37
2.12.1.4	BET MODEL.....	37
2.12.1.5	HARKINS-HENDERSON MODEL.....	37
2.12.1.6	REDLICH-PETERSON MODEL.....	37
2.12.1.7	TOTH MODEL.....	38
2.12.1.8	RADKE-PRAUNSHITZ MODEL.....	38
2.12.1.9	SIPS MODL.....	38
2.12.1.10	KHAN MODEL.....	38
2.12.1.11	DUBININ-RADUSKEVCH MODEL.....	39
2.12.1.12	KOBLE-CORRIGAN MODEL.....	39
2.12.2	MULTI-COMPONENT ISOTHERM MODELS.....	40
2.12.2.1	EXTENDED LANGMUIR MODEL.....	41
2.12.2.2	COMBINATION OF LANGMUIR-FREUNDLICH MODEL.....	41
2.12.2.3	REDLICH-PETERSON MODEL.....	41
2.12.2.4	EXTENDED FREUNDLICH MODEL.....	42
2.12.2.5	MODIFIED TEMKIN MODEL.....	42
2.12.2.6	HARKINS-JURA MODEL.....	42
2.12.2.7	HALSEY AND HENDERSON MODEL.....	43
2.13	KINETIC MODELING OF ADSORPTION / BIOSORPTION.....	43
	IN BATCH SYSTEM	
2.13.1	PSEUDO-FIRST KINETIC MODEL.....	43
2.13.2	PSEUDO-SECOND ORDER KINETIC MODEL.....	44
2.13.3	WEBER AND MORRIS INTRA-PARTICLE DIFFUSION MODEL..	45
2.13.4	ELOVICH KINETIC MODEL.....	45
2.13.5	FRACTIONAL POWER KINETIC MODEL.....	46
2.14	ADSORPTION / BIOSORPTION THERMODYNAMIC.....	46
2.15	DESORPTION AND REGENERATION OF BIOMASS.....	47
2.16	BATCH ADSORBER.....	48
2.17	COMPETITIVE ADSORPTION.....	48
2.18	ADSORPTION CAPACITY.....	49
2.19	ANALYTICAL MATHEMATICAL MODELS OF THE.....	50

FIXED-BED ADSORBER	
2.19.1 THOMAS MODEL.....	50
2.19.2 ADAMS-BOHART MODEL.....	50
2.19.3 WOLBORSKA MODEL.....	51
2.19.4 CLARK MODEL.....	51
2.19.5. YOON-NELSON MODEL.....	52
2.19.6 EQUILIBRIUM COLUMN MODEL (ECM).....	52
2.19.7 MASS TRANSFER COLUMN MODEL (MTCM).....	53
2.19.8 HOMOGENEOUS SURFACE DIFFUSION MODEL (HSDM).....	53
2.19.9 GENERAL MULTI-COMPONENT RATE MODEL (GMRM).....	53
CHAPTER THREE: MATHEMATICAL MODEL.....	54
3.1 INTRODUCTION.....	54
3.2 GENERAL MULTI-COMPONENT RATE MODEL (GMRM).....	54
3.3 MODEL ASSUMPTION.....	55
3.4 GENERAL RATE MODEL .FORMULATION.....	56
3.4.1 CONTINUITY EQUATION IN THE BULK-FLUID PHASE.....	56
3.4.2 CONTINUITY EQUATION INSIDE THE MACRO-PORES.....	58
3.4.3 INITIAL AND BOUNDARY CONDITIONS.....	59
3.4.3.1 INITIAL CONDITION.....	59
3.4.3.2 BOUNDARY CONDITION.....	59
3.4.4 DIMENSIONLESS GROUPS.....	59
3.5 NUMERICAL SOLUTION TO THE PARTIAL DIFFERENTIAL.....	61
EQUATIONS SYSTEM	
3.5.1 SOLUTION OF THE PDE SYSTEM USING MATLAB PROGRAM.....	62
3.5.1.1. FINITE ELEMENT FORMULATION FOR THE BULK... FLUID PHASE GOVERNIING EQUATION	62
3.5.1.2. ORTHOGONAL COLLECTION FORMULATION OF... THE PARTICLE PHASE GOVERNING EQUATION	63
CHAPTER FOUR: EXPERIMENTAL WORK.....	65
4.1 INTRODUCTION.....	65
4.2 MATERIALS.....	65
4.2.1 ADSORBATE.....	65
4.2.2 ADSORBENT AND BIOSORBENT.....	66
4.2.2.1. ADSORBENT " GRANULAR ACTIVATED CARBON (GAC)'.....	66
4.2.2.2. BIOSORBENT "WASTE OF FUNGI ".....	67

4.3 EQUIPMENT.....	69
4.4 EXPERIMENTAL ARRANGEMENTS.....	71
4.4.1. BATCH EXPERIMENTS.....	71
4.4.2. EXPERIMENTAL PROCEDURE.....	71
4.4.3. EFFECT OF VARIABLES.....	72
4.4.3.1. DETERMINATION OF BEST pH AND DOSE.....	72
4.4.3.2. DETERMINATION OF BEST CONTACT TIME.....	72
4.4.3.3. EFFECT OF INITIAL CONCENTRATION OF SOLUTIONS.....	72
4.4.4. EQUILIBRIUM ISOTHERM EXPERIMENTS.....	74
4.5 DESORPTION.....	74
4.6 DETERMINATION THERMODYNAMIC PARAMETERS OF.....	74
ADSORPTION / BIOSORPTION	
4.7 FOURIER-TRANSFORM INFRARED ANALYSIS (FTIR)	74
4.8 KINETIC EXPERIMENT.....	75
4.8.1. DETERMINATION OF THE OPTIMUM WEIGHT OF GAC/W.F.....	75
4.8.2. DETERMINATION OF THE BEST AGITATION SPEED.....	76
4.8.3. DETERMINATION OF THE EXTERNAL MASS.....	76
TRANSFER COEFFICIENT AND PORE DIFFUSION COEFFICIENT	
4.9 FIXED-BED COLUMN EXPERIMENTS.....	77
4.9.1. EXPERIMENTAL ARRANGEMENTS.....	77
4.9.2. FIXED-BED ADSORBER EXPERIMENTAL PROCEDURE.....	78
CHAPTER FIVE: RESULTS AND DISCUSSION.....	82
5.1 BATCH EXPERIMENTS.....	82
5.1.1 EFFECT OF pH.....	82
5.1.2. EFFECT OF CONTACT TIME.....	88
5.1.3. EFFECT OF ADSORBENT / BIOSORBENT DOSE.....	90
5.1.4. EFFECT OF INITIAL CONCENTRATION OF SOLUTION.....	92
5.2 ESTIMATION OF ADSORPTION / BIOSORPTION.....	97
ISOTHERMS CONSTANTS	
5.2.1. SINGLE COMPONENT SYSTEM.....	97
5.2.1.1. SINGLE COMPONENT SYSTEM USING GAC.....	98
5.2.1.2. SINGLE COMPONENT SYSTEM USING W.F.....	104
5.2.1.3. COMPARISON BETWEEN ISOTHERMS OF	109
HEAVY METAL IONS ONTO GAC AND W.F	
5.2.2. ISOTHERMS OF MULTI-COMPONENT SYSTEMS.....	112

5.2.2.1. BINARY COMPONENT SYSTEM.....	112
5.2.2.2. TERNARY COMPONENT SYSTEM.....	121
5.2.2.3. QUATERNARY COMPONENT SYSTEM.....	127
5.3 ADSORPTION / BIOSORPTION KINETICS.....	144
5.3.1. BEST WEIGHT OF ADSORBENT / BIOSORBENT.....	144
5.3.2. BEST AGITATION SPEED.....	145
5.3.3. ESTIMATION OF EXTERNAL MASS TRANSFER COEFFICIENT..	149
5.3.4. ESTIMATION OF AXIAL DISPERSION COEFFICIENT.....	150
5.3.5. KINETIC MODELS.....	150
5.4 FOURIER-TRANSFORM INFRARED ANALYSIS (FT-IR).....	157
5.5 THERMODYNAMIC PARAMETERS FOR FROM	164
ADSORPTION / BIOSORPTION PROCESS	
5.6 DESORPTION AND REGENERATION.....	167
5.7 FIXED-BED EXPERIMENTS (COLUMN STUDIES).....	169
5.7.1 SINGLE COMPONENT SYSTEM.....	169
5.7.1.1. EFFECT OF FLOW RATE.....	170
5.7.1.2. EFFECT OF BED-HEIGHT.....	176
5.7.1.3. EFFECT OF INITIAL CONCENTRATION.....	182
5.7.2. MULTI-COMPONENT ADSORPTION / BIOSORPTION.....	188
5.7.2.1. BINARY COMPONENT SYSTEM.....	188
5.7.2.2. TERNARY COMPONENT SYSTEM.....	196
5.7.2.3. QUATERNARY COMPONENT SYSTEM.....	201
CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS.....	204
6.1 BATCH SYSTEM.....	204
6.1.1. SINGLE COMPONENT SYSTEM.....	204
6.1.2. MULTI-COMPONENT SYSTEM.....	205
6.2 FIXED-BED COLUMNS.....	206
6.2.1. SINGLE COMPONENT SYSTEM.....	206
6.2.2. MULTI-COMPONENT SYSTEM.....	206
6.3 RECOMMENDATIONS FOR FUTURE STUDY.....	207
REFERENCES.....	208
APPENDICES.....	228
APPENDIX A EFFECT OF OPTIMUM PARAMETERS.....	228
APPENDIX B BATCH EXPERIMENTAL DATA.....	235
APPENDIX C CONCENTRATION-TIME DECAY CURVES.....	246

APPENDIX D	SAMPLE OF CALCULATIONS.....	250
APPENDIX E	BREATHROUGH DATA.....	254
APPENDIX F	PICTURES OF FT-IR SPECTRUM FOR.....	286
	LOADED GAC/W.F	
APPENDIX G	PAPERS EXTRACTED FROM THE PRESENT ph. D THESIS.	294

List of Tables

Table 1.1	Types of heavy metals and effects of human beings.....	3
Table 2.1	Treatment processes for the removal of heavy metals.....	9
Table 2.2	Physical and chemical adsorption properties for different parameters.....	11
Table 2.3	IUPAC classification of pore size.....	13
Table 2.4	Types of native biomass used for preparing biosorbents1.....	18
Table 2.5	Comparative between biosorption and bioaccumulation.....	18
Table 2.6	Effect of increasing value of input parameters on break point.....	34
Table 2.7	Values of separation factor and type of isotherm.....	36
Table 2.8	Adsorption isotherm models characteristics.....	40
Table 4.1	Metal ion salts.....	65
Table 4.2	Physical properties of activated carbon.....	66
Table 4.3	Physical properties of waste of Fungi.....	68
Table 4.4	Experimental conditions for continuous experiments.....	76
Table 5.1	Optimum conditions used to remove heavy metals from wastewater.....	97
Table 5.2	Isotherm parameters for single metal ions adsorbed onto GAC.....	103
Table 5.3	Isotherm parameters for single metal ions adsorbed onto W.F.....	108
Table 5.4	Parameters of a binary solute isotherm for metal ions onto GAC....	116
Table 5.5	Parameters of a binary solute isotherm for metal ions onto W.F.....	120
Table 5.6	Parameters of a ternary solute isotherm metal ions onto GAC.....	123
Table 5.7	Parameters of a ternary solute isotherm for metal ions onto W.F....	127
Table 5.8	Parameters of a quaternary solute isotherm for metal ions onto GAC.....	128
Table 5.9	Parameters of a quaternary solute isotherm for metal ions onto W.F.....	128
Table 5.10	Competition results in single, binary, ternary and quaternary systems using GAC.....	135
Table 5.11	Competition results in single, binary, ternary and quaternary systems using W.F.....	137
Table 5.12	Percentage reduced of the metal uptake capacity in binary, ternary and quaternary system compared with single system using A.C.....	139
Table5.13	Percentage reduced of the metal uptake capacity in binary, ternary	139

	and quaternary system compared with single system using W.F.....	
Table 5.1	Maximum removal efficiency of each pollutant using GAC.....	140
Table 5.1	Maximum removal efficiency of each pollutant using W.F.....	141
Table 5.16	Optimum weight of A.C. /W.F. used to reach final related concentration of $C_t/C_0 = 0.05$	144
Table 5.17	External mass transfer coefficient for Pb, Cu, Co, Cd ions onto GAC /W.F.....	149
Table 5.18	Kinetic model parameters for Pb(II), Cu(II), Co(II) and Cd(II) ions adsorption onto A.C.....	156
Table 5.19	Kinetic model parameters for Pb(II), Cu(II), Co(II) and Cd(II) ions adsorption onto waste of fungi	156
Table 5.20	FT-IR analysis for raw and loaded GAC.....	160
Table 5.21	FT-IR analysis for raw and loaded W.F.....	162
Table 5.22	Approximate assignment of the main bands in GAC IR spectra.....	163
Table 5.23	Approximate assignment of the main bands in W.F. IR spectra.....	163
Table 5.24	Thermodynamic parameters for the adsorption of Pb(II), Cu(II), Co(II) and Cd(II) onto A.C.....	165
Table 5.25	Thermodynamic parameters for the adsorption of Pb(II), Cu(II), Co(II) and Cd(II) onto W.F.....	165
Table 5.26	Thomas model parameters using linear regression analysis for metal ion adsorption under different flow rates.....	171
Table 5.27	Thomas model parameters using linear regression analysis for metal ion adsorption under different bed-heights.....	177
Table 5.28	Thomas model parameters using linear regression analysis for metal ion adsorption under different initial concentrations.....	183
Table 5.29	Thomas model parameters using linear regression analysis for metal ion adsorption in binary system.....	189
Table 5.30	Thomas model parameters using linear regression analysis for metal ion adsorption in ternary system.....	196
Table 5.31	Thomas model parameters using linear regression analysis for metal ion adsorption in quaternary system.....	201

List of Figures

Figure 2.1	Schema of the mechanism of molecule adsorption using..... microporous adsorbent	12
Figure 2.2	Schematic representation of external and internal adsorbent surface	14
Figure 2.3	Schematic of the process of activated carbon..... manufacturing	16
Figure 2.4	Cell wall structure in A: Algae, B: Fungi, C: Bacteria.....	21
Figure 2.5	Biosorption mechanisms.....	27
Figure 2.6	Typical breakthrough profile from a column study.....	33
Figure 2.7	Types of adsorption equilibrium isotherm relation.....	35
Figure 2.8	Breakthrough curve for multicomponent competitive..... adsorption	49
Figure 3.1	Schematic diagram describing mass transfer mechanisms in fixed bed adsorption column	56
Figure 3.2	Computer flow diagram of the numerical method.....	64
Figure 4.1	Sample of GAC used.....	66
Figure 4.2	Scanning electron micrographs for GAC.....	67
Figure 4.3	Untreated fungal waste biomass.....	68
Figure 4.4	A sample of treated fungal waste biomass.....	68
Figure 4.5	Scanning electron micrographs for waste of fungi.....	69
Figure 4.6	The equipment and measurement devices.....	70
Figure 4.7	Atomic Absorption spectrophotometer.....	71
Figure 4.8	Schematic diagram of batch adsorption/biosorption isotherm equilibrium procedure	73
Figure 4.9	Schematic of the kinetic experimental batch process.....	75
Figure 4.10	Unit of kinetic experiments.....	77
Figure 4.11	Schematic diagram of fixed bed adsorber.....	79
Figure 4.12	Pilot plant of fixed-bed reactor.....	80
Figure 4.13	Parts of arrangement of pilot plant.....	81
Figure 5.1	Optimum pH with optimum dose of GAC to remove Pb.....	83
Figure 5.2	Optimum pH with optimum dose of GAC to remove Cu.....	83
Figure 5.3	Optimum pH with optimum dose of GAC to remove Co.....	84
Figure 5.4	Optimum pH with optimum dose of GAC to remove Cd.....	84
Figure 5.5	Effect of pH of the solution on adsorption of heavy metals... used GAC	85

Figure 5.6	Optimum pH with optimum dose of W.F. to remove Pb.....	85
Figure 5.7	Optimum pH with optimum dose of W.F. to remove Cu.....	86
Figure 5.8	Optimum pH with optimum dose of W.F. to remove Co.....	86
Figure 5.9	Optimum pH with optimum dose of W.F. to remove Cd.....	87
Figure 5.10	Effect of pH of the solution on adsorption of heavy metals... used W.F.	87
Figure 5.11	Effect of contact time with % removal of adsorption of Pb(II), Cu(II), Co(II) and Cd(II) ions onto GAC at optimum dose & pH	88
Figure 5.12	Effect of contact time with uptake capacity of adsorption..... of Pb(II), Cu(II), Co(II) and Cd(II) ions onto GAC at optimum dose & pH	88
Figure 5.13	Effect of contact time with percentage removal of adsorption of Pb(II), Cu(II), Co(II) and Cd(II) ions onto W.F. at optimum dose & pH	89
Figure 5.14	Effect of contact time with uptake removal of adsorption..... of Pb(II), Cu(II), Co(II) and Cd(II) ions onto W.F. at optimum dose & pH	89
Figure 5.15	Effect of mass of GAC on percentage removal of Pb(II),..... Cu(II),Co(II) and Cd(II) ions at optimum pH	90
Figure 5.16	Effect of mass of GAC on uptake capacity of Pb(II),..... Cu(II),Co(II) and Cd(II) ions at optimum pH	91
Figure 5.17	Effect of mass of W.F. on percentage removal of Pb(II),..... Cu(II),Co(II) and Cd(II) ions at optimum pH	91
Figure 5.18	Effect of mass of W.F. on uptake capacity of Pb(II),..... Cu(II),Co(II) and Cd(II) ions at optimum pH	92
Figure 5.19	Effect of initial concentration of Pb(II) ions using GAC.....	93
Figure 5.20	Effect of initial concentration of Pb(II) ions using W.F.....	93
Figure 5.21	Effect of initial concentration of Cu (II) ions using GAC.....	94
Figure 5.22	Effect of initial concentration of Cu(II) ions using W.F.....	94
Figure 5.23	Effect of initial concentration of Co (II) ions using GAC.....	95
Figure 5.24	Effect of initial concentration of Co (II) ions using W.F.....	95
Figure 5.25	Effect of initial concentration of Cd(II) ions using GAC.....	96
Figure 5.26	Effect of initial concentration of Cd(II) ions using W.F.....	96
Figure 5.27	Adsorption isotherm for single component system of..... Pb ⁺² , Cu ⁺² , Co ⁺² and Cd ⁺² onto GAC	98
Figure 5.28	Adsorption isotherm for Pb(II) onto GAC.....	99
Figure 5.29	Adsorption isotherm for Cu (II) onto GAC.....	99
Figure 5.30	Adsorption isotherm for Co(II) onto GAC.....	100
Figure 5.31	Adsorption isotherm for Cd(II) onto GAC.....	100
Figure 5.32	Single adsorption isotherm for Pb(II), Cu(II), Co(II)..... and Cd(II) onto GAC	101
Figure 5.33	Maximum uptake capacity of Pb ⁺² , Cu ⁺² , Co ⁺² and	101