

Table of Contents

CERTIFICATE	2
DECLARATION BY THE CANDIDATE	3
COPYRIGHT TRANSFER CERTIFICATE	4
ACKNOWLEDGEMENT	5
ABSTRACT	11
LIST OF FIGURES	13
LIST OF TABLES	16
1 Introduction	17
1.1 Dyes and their classification	18
1.2 Treatment of the Dyeing Wastewater and Current Challenges	21
1.3 Objectives and Scope of the Study	22
1.4 Organization of Thesis	23
2 Literature on the treatment methodologies for removal of dyes from the wastewater	25
2.1 Physical Methods	26
2.2 Biological Methods	27
2.3 Chemical Methods	30
2.3.1 Fenton process	31
2.3.2 Photo-catalysis process	33
2.3.3 Ozonation process	35
2.4 Integration of the AOPs with biological methods	37
2.4.1 Integration of Fenton with biodegradation	38

2.4.2	Integration of photocatalysis with biodegradation	39
2.4.3	Integration of ozonation with biodegradation	40
3	Material and Methods	43
3.1	Materials and Chemicals	43
3.2	Preparation of synthetic dye wastewater	44
3.3	Molecular characterization of the efficient isolated bacteria	44
3.4	Biodegradation experiments in a batch reactor	45
3.5	Bioreactor configuration and immobilization of packing material	46
3.6	Analytical methods	47
3.6.1	UV-Vis Spectrophotometry	47
3.6.2	Biochemical Oxygen Demand (BOD)	47
3.6.3	Chemical Oxygen Demand (COD)	48
3.6.4	Total Organic Carbon (TOC)	48
3.8	Toxicity Analysis	49
3.8.1	Phytotoxicity	49
3.8.2	Bacterial toxicity	49
4	Improved Bacterial Growth Kinetic Model using Indigenously Isolated Strain <i>Bacillus Subtilis</i> MN372379 in the Degradation of Congo Red Dye	51
4.1	The conventional approach to determine the bacterial growth rate	52
4.2	Time-Averaged Bacterial Growth Rate Incorporating the Metabolite Inhibition: an Improved Approach Proposed in the Present Study	54
4.3	Time-averaged substrate utilization rate: An approach proposed in the present study	56

4.4	Identification of the Efficient Dye-Degrading Bacterial Isolate	57
4.5	Bacterial Growth Kinetics	58
4.5.1	Degradation of the Synthetic Wastewater at Different Initial Dye Concentrations	58
4.5.2	Determination of the specific bacterial growth rate time-averaged over the entire log phase for incorporating metabolite inhibition	60
4.5.3	Nature of metabolite inhibition in the decelerating part of log phase	62
4.5.4	Incorporation of time-averaged bacterial growth rate accounting metabolite inhibition in the bacterial growth models with substrate inhibition	63
4.6	Process optimization for the maximum dye utilization	66
4.6.1	Optimization of the initial dye concentration	66
4.6.2	Optimization of the initial inoculum size	67
5	Investigation of External Mass Transfer during Biodegradation of Congo Red Dye in a Recirculating Packed Bed Bioreactor	71
5.1	Bioreactor configuration	73
5.2	Bacterial immobilization and acclimatization in the Congo Red dye environment in the RPBB	74
5.3	Mass Transfer Study: Theoretical Method	75
5.3.1	Concentration profile and observed biodegradation rate in the RPBB	75
5.3.2	Modification in the material balance equation to account for recirculation in an RPBB	76
5.3.3	Evaluation of external mass transfer in the RPBB	77
5.4	Results and Discussion	79
5.4.1	Effect of inlet mass flow rate on the overall rate of dye removal in the RPBB	80

5.4.2	Determination of the correlation for external mass transfer coefficient	81
5.4.3	Determination of the Colburn factor for external mass transfer coefficient	83
5.4.4	Effect of recirculation flow rate on the external mass transfer	84
5.5	Conclusion	85
6	Optimization for Minimizing the Cost of Ozonation of Highly Concentrated Textile Dyeing Wastewater in a Bubble Column Reactor	87
6.1	Experimental Setup	89
6.2	Design of experiment	90
6.3	Dye removal and electricity consumption at various initial dye concentration	91
6.4	Development of an empirical correlation for the average specific electricity consumption during the ozonation of Reactive Blue dye	93
6.4.1	Measurement of the SEC_{av} for the DOE	93
6.4.2	Statistical modeling for the SEC_{av} using RSM	94
6.5	Effect of process variables on the average specific electricity consumption in the ozonation of Reactive Blue dye	96
6.5.1	Effect of inlet ozone concentration	97
6.5.2	Effect of initial pH level	97
6.5.3	Effect of initial dye concentration	98
6.6	Optimization of process variables to minimize SEC_{av}	98
6.7	Model verification and cost analysis	99
6.8	Conclusion	100

7	Phyto-/Geno-Toxicity Assessments of the Dyeing Wastewater treated with Anaerobic-Aerobic Biodegradation (AnAB) vs. Ozonation-Aerobic Biodegradation (OAB) Processes	101
7.1	Configuration of AnAB and OAB systems	104
7.2	Bacterial immobilization and their acclimatization to the SDW in the FBBR	107
7.3	Performance evaluation of the hybrid AnAB and OAB systems	108
7.3.1	COD removal	108
7.3.2	Color removal	110
7.3.3	Overall Performance AnAB and OAB System against varied organic loading rates	111
7.4	Toxicity assessment	113
7.4.1	Phytotoxicity analysis	113
7.4.2	Bacterial toxicity analysis	115
7.5	Conclusion	118
8	Conclusion and Future Aspects	120
9	Bibliography	122
10	List of Publications	146