

ENVIRONMENTAL IMPACTS AND GREENHOUSE GAS EMISSIONS LIFE CYCLE ASSESSMENT OF WASTEWATER TREATMENT PLANTS

by Thi Kieu Loan Nguyen

Thesis submitted in fulfilment of the requirements for
the degree of

Doctor of Philosophy

under the supervision of
Prof. Huu Hao Ngo, Prof. Wenshan Guo, and Dr. Vinh Tien
Nguyen

University of Technology Sydney
Faculty of Engineering and Information Technology

July, 2021

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Thi Kieu Loan Nguyen, declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology at the University Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certified that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

Signature: Production Note:
Signature removed prior to publication.

Date: 11/7/2021

ACKNOWLEDGMENTS

First and foremost, I would like to take this opportunity to express my sincerest gratitude to my supervisors Prof. Huu Hao Ngo, Prof. Wenshan Guo, and Dr. Vinh Tien Nguyen. Without their dedicated guidance and continuous support, this thesis would not have been accomplished. My most profound appreciation and heartfelt thanks go to my principal supervisor, Prof. Huu Hao Ngo. He was the one who guides me, help me in my Ph.D. journey with his insightful vision, invaluable advice, and endless support. He has spending hours suggesting my directions, revise my journal papers and my thesis. His noble personality and positive energy deeply impressed me. Not only being a supervisor, but he is also an understandable friend. His endless help and warm encouragement took me to overcome the difficulties in academics and stress in my life. Influenced by his optimism, I was confident enough to face the troubles then enjoy my Ph.D. student's life. I am also deeply grateful for my co-supervisor, Prof. Wenshan Guo and Dr. Vinh Tien Nguyen, whose constructive comments and inspirations were essential to completing my thesis.

I would like to acknowledge the Vietnam International Education Development (VIED) for awarding me the 911 scholarship and the University of Technology Sydney (UTS) for providing me the International Research Scholarship.

My special thanks also to Thuy Nguyen Hong Le for lending me SimaPro software, making my research more valuable and precise. I am thankful to the academic and administrative staff from the Faculty of Engineering and Information Technology and the Graduate Research School of UTS, and Hanoi Architectural University. During my student years at UTS, I was fortunate to meet my excellent groupmates, including Dora, Khan, Jerry, and Phong, who share their interests and experiences. My warm thanks are

for my friends, Lan Uong, Hang Do, Allie Nguyen, Quyen Nguyen, Thuy Nguyen, An Le, who have been sharing the joy and sorrow with me.

Most importantly, none of this could have happened without my family, who are the most ardent supporters of my study. My parents made phone calls every week to encourage me, gave me unconditional sacrifice. My husband stayed side by my side, providing me unfailing support. They are my love, my strength, and my motivation in my life. My last but not least words are for my kids, Sally and Mark, who have been accompanying me since I first came to Australia. This thesis is dedicated to my family and my two little sweeties.

TABLE OF CONTENT

CERTIFICATE OF ORIGINAL AUTHORSHIP.....	i
ACKNOWLEDGMENTS.....	ii
LIST OF TABLES.....	vii
LIST OF FIGURES.....	ix
LIST OF ABBREVIATIONS.....	xii
ABSTRACT.....	xiii
Chapter 1	1-1
INTRODUCTION	1-1
1.1. OVERVIEW.....	1-2
1.1. RESEARCH SCOPE AND OBJECTIVES	1-4
1.2. RESEARCH NOVELTY AND SIGNIFICANCE	1-5
1.3. THESIS STRUCTURE.....	1-5
Chapter 2	2-1
LITERATURE REVIEW.....	2-1
2.1. INTRODUCTION.....	2-2
2.2. GHG EMISSIONS FROM WASTEWATER SECTOR.....	2-3
2.3. DIRECT EMISSIONS FROM AAO TREATMENT PROCESS	2-9
2.3.1. Methane emissions	2-10
2.3.2. Carbon dioxide.....	2-12
2.3.3. Nitrous oxide	2-14
2.4. GHG EMISSIONS FROM SBR PROCESS.....	2-16
2.4.1. Methane emission.....	2-17
2.4.2. Carbon dioxide.....	2-18
2.4.3. Nitrous oxide	2-19
2.5. GHG EMISSIONS QUANTIFICATION METHODS.....	2-22
2.5.1. Direct measurement.....	2-22
2.5.2. Guideline tool	2-24
2.5.3. Modelling tool	2-30
2.6. CHALLENGES IN QUANTIFYING GHG EMISSIONS FROM TREATMENT PROCESS	2-33
2.7. ENVIRONMENTAL IMPACTS ASSESSMENT FOR WWTP.....	2-37
2.7.1. The current use of LCA applications to WWTP	2-37
2.7.2. Integration of LCA and GHG quantification method.....	2-47
2.8. CONCLUSIONS	2-50
Chapter 3	3-1
RESEARCH METHODOLOGY	3-1
3.1. INTRODUCTION.....	3-2
3.2. LIFE CYCLE IMPACTS ASSESSMENT METHOD	3-2
3.2.1. Goal and scope definition.....	3-2

3.2.2. Life cycle inventory analysis	3-33
3.2.3. Life cycle impact assessment.....	3-5
3.2.4. Improvement analysis and interpretation	3-6
3.3. ENVIRONMENTAL IMPACT METHODS AND CATEGORIES	3-7
3.3.1. EDP 2018.....	3-7
3.3.2. ReCiPe 2016	3-77
3.4. ANALYTICAL SOFTWARE.....	3-10
Chapter 4	4-1
CONTRIBUTION OF THE CONSTRUCTION PHASE TO ENVIRONMENTAL IMPACTS....	4-1
4.1. INTRODUCTION.....	4-2
4.2. MATERIALS AND METHODS	4-4
4.2.1. Life cycle assessment.....	4-4
4.2.2. Case study description	4-8
4.2.3. Environmental burdens caused by construction reported in the literature	4-8
4.3. RESULTS.....	4-13
4.3.1. Environmental impacts of Girona WWTP's construction	4-13
4.3.2. Contribution of construction at Mill Creek WWTP	4-8
4.4. DISCUSSION.....	4-19
4.4.1. Influence of materials to impact categories	4-19
4.4.2. Reinforcing steel, concrete, and their environmental impacts	4-21
4.4.3. The impact of individual treatment unit on the construction phase	4-23
4.5. CONCLUSIONS	4-24
Chapter 5	5-1
ANALYSING THE GREENHOUSE GAS EMISSIONS AND CUMULATIVE ENERGY DEMAND BASED ENVIRONMENTAL IMPACTS	5-1
5.1. INTRODUCTION.....	5-2
5.2. MATERIALS AND METHODS	5-4
5.2.1. Goal and scope	5-4
5.2.2. Life cycle inventory.....	5-5
5.3. RESULTS AND DISCUSSIONS	5-10
5.3.1. Environmental impacts assessment for the operation phase.....	5-10
5.3.2. GHG Protocol assessment.....	5-15
5.3.3. Cumulative energy demand analysis	5-16
5.3.4. Uncertainty analysis.....	5-17
5.4. CONCLUSIONS	5-18
Chapter 6	6-1
ASSESSING THE ENVIRONMENTAL IMPACTS AND GREENHOUSE GAS EMISSIONS FROM THE COMMON MUNICIPAL WASTEWATER TREATMENT PLANT	6-1
6.1. INTRODUCTION.....	6-2
6.2. MATERIALS AND METHODS	6-4

6.2.1. Case study description	6-4
6.2.2. Life cycle assessment.....	6-5
6.3. RESULTS AND DISCUSSIONS	6-9
6.3.1. Contribution of construction and operation phases to environmental problems	6-9
6.3.2. Environmental impacts and GHG assessment for conventional and nature-based WWTPs	6-15
6.4. CONCLUSIONS	6-21
Chapter 7	7-1
ENVIRONMENTAL IMPACTS AND GREENHOUSE GAS EMISSIONS ASSESSMENT FOR ENERGY RECOVERY AND MATERIAL RECYCLE	7-1
7.1. INTRODUCTION.....	7-2
7.2. MATERIALS AND METHODS	7-5
7.2.1. Recycle waste from construction demolitions activities	7-5
7.2.3. Life cycle assessment (LCA)	7-10
7.3. RESULTS AND DISCUSSIONS	7-15
7.3.1. Building materials recycling and environmental impacts	7-15
7.3.2. Environmental analysis for biogas utilization	7-19
7.4. INTERPRETATIONS AND DISCUSSIONS.....	7-21
7.4.1. Recycling – advantages and limitations	7-21
7.4.2. Energy recovery and GHG emissions mitigation	7-23
7.5. CONCLUSIONS	7-25
Chapter 8	8-1
CONCLUSIONS AND RECOMMENDATIONS	8-1
8.1. CONCLUSIONS	8-2
8.2. RECOMMENDATIONS	8-6
REFERENCES	R-1
APPENDIX.....	A-1

LIST OF TABLES

Table 2.1	Methane emitted from each zone. Source (Liu et al., 2014; Wang et al., 2011)	2-11
Table 2.2	CO ₂ emissions from each unit in the AAO treatment process, source (Bao et al., 2015; Yan et al., 2014)	2-13
Table 2.3	N ₂ O emission in AAO process, source (Ren et al., 2013; Sun et al., 2013a; Yan et al., 2014)	2-15
Table 2.4	N ₂ O emitted from each zone in SBR process, source (Bao et al., 2016; Sun et al., 2014; Sun et al., 2013a)	2-21
Table 2.5	Reviewed studies on the influence of DO, aeration efficiency and dissolved GHGs on GHGs	2-35
Table 2.6	Articles included in the review and main characteristics	2-39
Table 4.1	Summary of inventory for Girona WWTP	4-6
Table 4.2	Inventory for Mill Creek WWTP	4-6
Table 4.3	Characteristic of the case studies WWTPs	4-8
Table 4.4	Summary of LCA studies concerning the construction phase since 2015	4-16
Table 4.5	Reinforcing steel and concrete used for construction per functional unit (FU)	4-22
Table 4.6	Material usage in the primary and secondary treatment units	4-23
Table 5.1	Summary of the energy consumption in the case study	5-6
Table 5.2	Data inventory for case study WWTP, obtained from research of Morera et al. (2017)	5-8

Table 5.3	The proportion of the operation phase to the entire environmental impacts of the WWTP	5-14
Table 5.4	Component of GHG emissions from the treatment process	5-15
Table 5.5	Uncertainty analysis for data inventory per impact category	5-17
Table 6.1	Case study systems description	6-5
Table 6.2	Data inventory for each case study	6-6
Table 6.3	Damage assessment at endpoint level of the case studies	6-16
Table 6.4	Uncertainty analysis for CW and HRAP	6-19
Table 7.1	CDW disposal methods	7-10
Table 7.2	Bekkelaget WWTP characteristic	7-11
Table 7.3	The summary of construction data inventory for plant 1	7-13
Table 7.4	Data inventory for operation phase recover pathways in Plant 2	7-13
Table 7.5	Influence of production variation	7-24

LIST OF FIGURES

Figure 2.1	Global Methane Emission by sectors in 2012	2-5
Figure 2.2	Total global N ₂ O emission and N ₂ O emission from domestic wastewater	2-6
Figure 2.3	Global sewage CO ₂ production	2-7
Figure 2.4	Methane emitted from different units in the SRB process	2-18
Figure 2.5	Influences of processes condition to GHGEs	2-35
Figure 2.6	The advantages of using LCA in WWTPs	2-37
Figure 2.7	Level of LCA coverage in 25 reviewed papers	2-47
Figure 3.1	The connection between data inventories, midpoint, and endpoint indicators	3-9
Figure 4.1	Life Cycle Impact Assessment (LCIA) using EPD 2018 indicators for Girona WWTP	4-9
Figure 4.2	LCIA using ReCiPe 2016 indicators	4-10
Figure 4.3	LCIA using ReCiPe 2016 for a single unit in the construction of the Girona WWTP	4-11
Figure 4.4	ReCiPe method for construction material in Mill Creek WWTP	4-12
Figure 4.5	Contribution of the individual treatment unit	4-13
Figure 4.6	ReCiPe's weighted endpoint damage categories for case studies	4-14
Figure 4.7	Diesel's impacts in our study and that by Morera et al. (2020).	4-20
Figure 5.1	The environmental impacts of the operation phase	5-11
Figure 5.2	The proportion of troubles cause by WWTP through damage assessment	5-12
Figure 5.3	The percentage of trouble caused by materials through damage assessment	5-13

Figure 5.4	The proportion of energy type utilized in treatment processes	5-16
Figure 6.1	(A) LCIA for AS; (B) LCIA for CW; (C) LCIA for HRAP	6-10
Figure 6.2	Proportion of problems caused by construction and operation	6-14
Figure 6.3	Indicators corresponding to three areas of protection	6-18
Figure 6.4	GHG emissions evaluation using the GHG Protocol method	6-29
Figure 7.1	The proportion of recycled concrete and steel in some countries	7-7
Figure 7.2	LCIA for C+D in plant 1 – case B	7-17
Figure 7.3	GHG emissions and damage assessment	7-18
Figure 7.4	GHG emissions from biogas conversion methods	7-19
Figure 7.5	Environmental impact analysis for six scenarios	7-20
Figure 7.6	Uncertainty analysis for Case D	7-22

LIST OF ABBREVIATIONS

WWTPs	Wastewater Treatment Plants
MWWTPs	Municipal Wastewater Treatment Plants
GHG	Greenhouse Gas
COD	Chemical Oxygen Demand
TN	Total Nitrogen
BOD	Biochemical Oxygen Demand
DO	Dissolved Oxygen
SBR	Sequencing Batch Reactor
AAO	Anaerobic Anoxic Oxidation
IPCC	Intergovernmental Panel on Climate Change
HRT	Hydraulic Retention Time
GWP	Global Warming Potentials
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
BNR	Biological Nutrient Removal
ASM	Activated Sludge Model
BSM	Benchmark Simulation
BSM2G	Benchmark Simulation no.2 Gas
PAOs	Phosphorus Accumulating Organisms
ICA	Instrumentation, Control and Automation
CH ₄	Methane
N ₂ O	Nitrous oxide
CO ₂	Carbon dioxide

HH	Human health
TE	Terrestrial ecotoxicity
PE	Population equivalent
CO ₂ eq	Carbon dioxide equivalent
Mg	Milligram
T	Ton
m ³	Cubic meter
D	Day
Yr	Year
PM	Particular matter
I	Individualist
H	Hierarchist
E	Egalitarian
DALYs	Disability adjusted life years

Ph.D. DISSERTATION ABSTRACT

Author: Thi Kieu Loan Nguyen

Thesis title: ENVIRONMENTAL IMPACTS AND GREENHOUSE GAS EMISSIONS
LIFE CYCLE ASSESSMENT OF WASTEWATER TREATMENT
PLANTS

Faculty: Faculty of Environmental and Information Technology

School: Civil and Environmental Engineering

Supervisors: Prof. Huu Hao Ngo (Principal supervisor)
Prof. Wenshan Guo (Co-supervisor)
Dr. Tien Vinh Nguyen (Co-supervisor)

ABSTRACT

Due to the impact of methane, carbon dioxide, and nitrous oxide on global warming, the quantity of these greenhouse gases (GHG) emissions from municipal wastewater treatment plants (WWTPs) has attracted more and more attentions. For decades, there has been a strong interest in mitigating greenhouse gas (GHG) emissions from wastewater treatment plants (WWTPs). The amount of GHG emitted depends on the influent and effluent characteristics, type of energy, and operation condition. Numerous tools have been developed to measure the emissions and propose the quantification, while Life Cycle Assessment (LCA) assesses the potential environmental impacts. However, the current knowledge for suggesting proper strategies towards sustainable development for WWTP is still limited due to the complex situation.

This thesis investigated the environmental issues concerning the construction, operation, and demolition phases of the WWTP. Production and end-of-life solution activities for material, chemicals, energy, and all treatment processes were considered for the

research. Detailed data inventories for various type of wastewater treatment systems, consists of natural-based and activated-based, were collected for calculation. ReCiPe 2016, EPD 2018, and TRACI life cycle impact assessment methods were employed via SimaPro 9.1 to measure all impact categories at both midpoint and endpoint levels. Two single-issue approaches, including Greenhouse Gas Protocol and Cumulative Energy Demand, were applied to support the results ensuring the hypotheses.

The uncertainty analyses presented the accuracy of data, which significantly influenced the outcomes of the LCA. Obtaining information from other studies or using representative data from a single unit led to imprecision results. Therefore, the inclusion of construction and demolition phases in the assessment is vital. Moreover, results show that 12.8% of the total impacts were generated by construction and destruction activities. Their consequences on ozone depletion were 34%. The main contributors for the construction and demolition stage are concrete and reinforcing steel, while electricity and sludge are responsible for operation phase problems. It was found that operation period creates the most significant burdens and GHG emissions due to 90% of consumed energy are non-renewable fossil type.

Regarding the benefit of nature and GHG emissions mitigation, materials recycling and different biogas conversion techniques are considered. The thesis concludes that 100% of recycled concrete and metal could reduce 4 kttons of CO₂ equivalent. The method of producing electricity and heat from biogas for internal utilization becomes the most optimistic when being avoided 115 g of CO₂ per m³ of wastewater.