

**SUSTAINABLE PROCESS DESIGN OF BIOFUELS :
BIOETHANOL PRODUCTION FROM CASSAVA RHIZOME**

Saranya Mangnimit

A Thesis Submitted in Partial Fulfilment of the Requirements
for the Degree of Master of Science
The Petroleum and Petrochemical College, Chulalongkorn University
in Academic Partnership with
The University of Michigan, The University of Oklahoma,
Case Western Reserve University, and Institut Français du Pétrole
2013

I 2837 2220

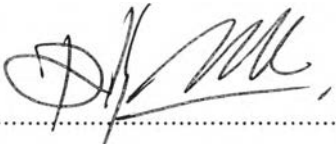
560999

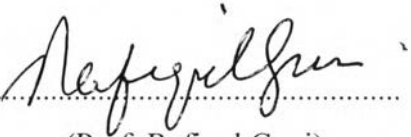
Thesis Title: Sustainable Process Design of Biofuels :
Bioethanol Production from Cassava Rhizome
By: Saranya Mangnimit
Program: Petroleum Technology
Thesis Advisors: Asst. Prof. Pomthong Malakul
Prof. Rafiqul Gani

Accepted by The Petroleum and Petrochemical College, Chulalongkorn University, in partial fulfilment of the requirements for the Degree of Master of Science.

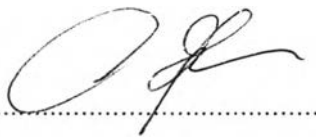

..... College Dean
(Asst. Prof. Pomthong Malakul)

Thesis Committee:


.....
(Asst. Prof. Pomthong Malakul)


.....
(Prof. Rafiqul Gani)


.....
(Asst. Prof. Kitipat Siemanond)


.....
(Dr. Vorakan Burapatana)

ABSTRACT

5473020063: Petroleum Technology Program

Saranya Mangnimit: Sustainable Process Design of Biofuel:

Bioethanol Production from Cassava Rhizome

Thesis Advisors: Asst. Prof. Pomthong Malakul and Prof. Rafiqul

Gani 151 pp.

Keywords: Sustainable process design/ Bioethanol/ Cassava rhizome/ Economic evaluation/ Life cycle assessment

This study focused on the sustainable process design of bioethanol production from cassava rhizome using various tools, including process simulation, sustainability analysis, economic evaluation and life cycle assessment (LCA). The process simulator program, PRO/II 9.1, was used to generate a base case design of the bioethanol conversion process using cassava rhizome as a feedstock. The sustainability analysis software, SustainPro, was then used to analyze relevant indicators in sustainability metrics, which were further employed to provide directions for improvements. To evaluate profitability of the process, ECON software was employed. Lastly, the life cycle environmental impact associated with bioethanol production was evaluated by using LCA software, SimaPro 7.1. Several alternative designs were generated and compared with the base case design in terms of economics, energy and environment in order to identify the most sustainable design for the production of ethanol with a capacity of 150,000 liters/day of ethanol production from cassava rhizome. Based on SustainPro results, three ideas of new design alternatives were generated for possible improvement. The ideas were heat integration to reduce energy; wastewater recovery using membranes; and the combustion of lignin as fuel. Based on these ideas, seven alternative designs were generated from different combinations of these ideas. Finally, all alternatives were compared with the base case design to show the improvements of these designs for more sustainable.

บทคัดย่อ

ศรัณญา มั่งนิมิตร : การออกแบบกระบวนการผลิตเชื้อเพลิงชีวภาพอย่างยั่งยืน : การผลิตไบโอเอทานอลจากเหง้ามันสำปะหลัง (Sustainable Process Design of Biofuel: Bioethanol Production from Cassava Rhizome) อาจารย์ที่ปรึกษา : ผศ. ดร. ปมทอง มาลากุล ณ อยุธยา และ ศ. ดร. ราฟีก กานี 151 หน้า

งานวิจัยนี้มุ่งเน้นศึกษาการออกแบบกระบวนการผลิตไบโอเอทานอลจากเหง้ามันสำปะหลังอย่างยั่งยืนโดยใช้เครื่องมือหลายประเภท ได้แก่ การจำลองกระบวนการผลิต การวิเคราะห์ความยั่งยืน การวิเคราะห์เชิงเศรษฐศาสตร์ และการประเมินวัฏจักรชีวิต (LCA) โปรแกรม PRO/II 9.1 ได้ถูกนำมาใช้ในการสร้างแบบจำลองพื้นฐานสำหรับกระบวนการผลิตไบโอเอทานอลโดยใช้เหง้ามันสำปะหลังเป็นวัตถุดิบ จากนั้นโปรแกรมวิเคราะห์ความยั่งยืน SustainPro จึงถูกนำมาใช้ในการวิเคราะห์ตัวชี้วัดด้านความยั่งยืนเพื่อนำมาหาแนวทางปรับปรุงแบบจำลองกระบวนการ สำหรับการวิเคราะห์ผลกำไรของกระบวนการนั้นใช้โปรแกรม ECON และท้ายสุดทำการประเมินผลกระทบต่อสิ่งแวดล้อมด้วยโปรแกรมประเมินวัฏจักรชีวิต SimaPro 7.1 จากผลการวิเคราะห์ของโปรแกรม SustainPro แบบจำลองทางเลือกใหม่ได้ถูกสร้างขึ้นโดยอาศัยแนวความคิดหลักสามแบบเพื่อการปรับปรุง คือ การบูรณาการทางความร้อนเพื่อลดการใช้พลังงาน การนำน้ำทิ้งกลับมาใช้ใหม่โดยใช้เยื่อเลือกผ่าน และการนำลิกนินมาเผาไหม้เป็นเชื้อเพลิง จากแนวความคิดทั้งสาม สามารถนำมาผสมผสานกันได้แบบจำลองทางเลือกทั้งหมดเจ็ดทางเลือก จากนั้นจึงทำการเปรียบเทียบระหว่างแบบจำลองพื้นฐานกับแบบจำลองทางเลือกต่างๆ เพื่อแสดงให้เห็นถึงการปรับปรุงกระบวนการเพื่อให้เกิดความยั่งยืนขึ้น

ACKNOWLEDGEMENTS

This work would not have been possible without the assistance of the following individuals:

First and foremost, I sincerely appreciate Asst. Prof. Pomthong Malakul and Prof. Rafiqul Gani, my advisor for providing invaluable knowledge, creative comments, untouchable experience in classroom, giving me the best opportunity of visiting Computer Aided Process-Product Engineering Center (CAPEC), Technical University of Denmark, and kind support throughout this research work.

I would like to thank Asst. Prof. Kitipat Siemanond and Dr. Vorakan Burapatana for being my thesis committee. Their suggestions and comments are very beneficial for me and this work.

I would like to acknowledge to Mr. Patharutama Nidhinandana, Mr. Siwanat Chairakwongsa and Mr. Fabrício Rodrigues for the excellent supporting regarding PRO/II and SustainPro with patience and total availability to help.

This thesis work is funded by the Petroleum and Petrochemical College, Thailand. I would also like to thank Computer Aided Process Engineering Center, Technical University of Denmark for funding this thesis.

I greatly appreciate all PPC staffs and my friends who gave me support and encouragement.

Finally, I am deeply indebted to my family for their love, understanding, encouragement, and support for me at all time.

TABLE OF CONTENTS

	PAGE
Title Page	i
Abstract (in English)	iii
Abstract (in Thai)	iv
Acknowledgements	v
Table of Contents	vi
List of Tables	ix
List of Figures	xi
CHAPTER	
I INTRODUCTION	1
II LITERATURE REVIEW	3
2.1 Energy Situation in Thailand	3
2.1.1 Energy Consumption in Thailand	3
2.1.2 Petroleum in Thailand	5
2.1.3 Alternative and Renewable Energy	9
2.2 Biofuels	10
2.2.1 Biofuel Generations	10
2.2.2 Bioethanol Situation in Thailand	15
2.3 Biomass, Lignocellulosic Biomass and Agricultural Residues	19
2.3.1 Definition of Biomass	19
2.3.2 Categories of Biomass Materials	20
2.3.3 Application of Biomass Materials	20
2.3.4 Lignocellulosic-Based Bioethanol in Thailand	21
2.4 Sustainable Development	29
2.4.1 Definition of Sustainable Development	29
2.4.2 Sustainable Energy for Future	29

CHAPTER	PAGE
2.5 Life Cycle Assessment (LCA)	30
2.5.1 Definition of LCA	30
2.5.2 Overview of LCA	32
2.5.3 Methodology of LCA	33
2.5.4 LCA Studies on Bioethanol	36
III EXPERIMENTAL	40
3.1 Methods and Tools	40
3.1.1 Equipment	40
3.1.2 Software	40
3.2 Experimental Procedures	40
3.2.1 Literature Survey	40
3.2.2 Location of the Bioethanol Production from Cassava Rhizome Plant	40
3.2.3 Capacity of the Bioethanol Production from Cassava Rhizome Plant	41
3.2.4 Process Simulation	41
3.2.3 Sustainability Analysis	42
3.2.4 Life cycle Assessment (LCA)	42
3.2.5 Economic Evaluation	43
IV RESULTS AND DISCUSSION	44
4.1 Base Case Design	44
4.1.1 Process Simulation of Base Case Design	44
4.1.2 Sustainability Analysis of Base Case Design	49
4.1.3 Economic Evaluation of Base Case Design	53
4.1.4 Life Cycle Assessment of Base Case Design	60
4.2 Alternative Design Ideas	68
4.2.1 Base Case with Heat Integration	69
4.2.2 Wastewater Recover by Membrane	70
4.2.3 Lignin Combustion	72

CHAPTER	PAGE
4.3 Comparison Between Base Case and Alternatives	76
4.3.1 Water Consumption	76
4.3.2 Economic Evaluation Comparison	77
4.3.3 Life Cycle Assessment Comparison	81
4.3.4 Overall Comparison	87
V CONCLUSIONS AND RECOMMENDATIONS	89
REFERENCES	91
APPENDICES	96
Appendix A Components Considered in PRO/II	96
Appendix B Chemical Reactions Implemented in PRO/II	97
Appendix C Main Process Condition for Base Case Design	101
Appendix D Bioethanol Conversion Process Flowsheet and Stream Tables Implemented in PRO/II	103
Appendix E Economic Evaluation for Base Case Design	133
Appendix F System Boundary and Environmental Impact Results of New Design Alternatives	140
CURRICULUM VITAE	151

LIST OF TABLES

TABLE	PAGE
2.1 Thailand petroleum reserves in 2007	6
2.2 Classification of second generation biofuels from lignocellulosic feedstocks	14
2.3 Top world's ethanol production by country	16
2.4 Existing ethanol plants in Thailand	18
2.5 Contents of cellulose, hemicellulose and lignin in Thailand based lignocellulosic biomass (moisture free)	23
2.6 Energy potential of agricultural residues in Thailand	25
2.7 Comparison of GHG emission from difference sources	36
4.1 Sustainability results of the base case design	49
4.2 List of the sensitive indicators for the open-paths for the base case design	50
4.3 Open-paths, components, paths, indicators and scores paths in the process for the indicators chosen to further analyze as good targets for improvement	52
4.4 Profitability of the base case design	59
4.5 Results of the inventory analysis per one kilogram ethanol 99.5 wt% production in rice plantation stage for the base case design	62
4.6 Results of the inventory analysis per one kilogram ethanol 99.5 wt% production in transportation (one way) stage for the base case design	62

TABLE	PAGE
4.7 Results of the inventory analysis per one kilogram ethanol 99.5 wt% production in pretreatment stage for the base case design	63
4.8 Results of the inventory analysis per one kilogram ethanol 99.5 wt% production in detoxification stage for the base case design	63
4.9 Results of the inventory analysis per one kilogram ethanol 99.5 wt% production in SSCF fermentation stage for the base case design	64
4.10 Results of the inventory analysis per one kilogram ethanol 99.5 wt% production in distillation stage for the base case design	64
4.11 Results of the inventory analysis per one kilogram ethanol 99.5 wt% production in dehydration stage for the base case design	65
4.12 Results of the inventory analysis per one kilogram ethanol 99.5 wt% production in wastewater treatment stage for the base case design	65
4.13 Environmental impact of bioethanol conversion process from Cassava Rhizome per one kilogram ethanol 99.5 wt% of the base case design	66
4.14 Overall alternative designs	68
4.15 Hot and cold streams in each heat exchanger from the base case design	69
4.16 List of rank for the best alternative design for bioethanol production process from Cassava Rhizome	88

LIST OF FIGURES

FIGURE	PAGE
2.1 Final energy consumption, 2011	3
2.2 Final energy consumption by economic sector, 2011	4
2.3 Energy production by fuel type	5
2.4 Thailand crude oil production and consumption by year	7
2.5 Trend of NYMEX light sweet crude oil prices between 2000-2010	8
2.6 Petroleum product uses in Thailand	8
2.7 Alternative energy consumption in Thailand, 2011	9
2.8 Overview of the ethanol production process	11
2.9 The carbon cycle of biomass	19
2.10 Composition of lignocellulosic biomass	21
2.11 World producers of cassava by the major producing countries	26
2.12 World production of cassava by countries	26
2.13 The main operations of the bioethanol process from lignocellulosic biomass	28
2.14 Sustainable development concept	29
2.15 Structure of the life cycle assessment	31
2.16 Life cycle of biofuels	32
2.17 Life cycle assessment framework	35
2.18 Greenhouse gas emission of ethanol from sugarcane	37
2.19 The comparison (between allocation factors) of CO ₂ equivalent emission for ethanol production and main process involved	38
2.20 The characterized impact factor for natural regeneration scenario	39

FIGURE	PAGE
4.1 Base case process flowsheet of the bioethanol production process from Cassava Rhizome	45
4.2 Flowsheet of the bioethanol production process from Cassava Rhizome for the base case design implemented in POR/II	46
4.3 Breakdown of the total capital investment	53
4.4 Breakdown of direct cost	54
4.5 Breakdown of contribution to equipment costs of each area of the process	54
4.6 Breakdown of the total production cost	55
4.7 Breakdown of the contribution of raw materials for the production cost	56
4.8 Breakdown of the contribution of utilities for the production cost	57
4.9 Sensitivity analysis compare to NPV	58
4.10 Cumulative cash flow for 20 year project of the base case design	59
4.11 Five stage of the base case design life cycle	60
4.12 System boundary of the base case design	61
4.13 Distribution of environmental impacts classified stage by stage of the base case design	67
4.14 Heat exchanger network of the base case design	70
4.15 Flowsheet of the bioethanol production process from Cassava Rhizome for alternative 1 design	73
4.16 Flowsheet of the bioethanol production process from Cassava Rhizome for alternative 2 design	74
4.17 Flowsheet of the bioethanol production process from Cassava Rhizome for alternative 3 design	75

FIGURE	PAGE
4.18 Comparison the water saving compare to the base case design	76
4.19 Comparison of capital cost and operating cost of each design	77
4.20 Comparison of NPV of each design for 20 years life time	78
4.21 Comparison of IRR of each design for 20 years life time	78
4.22 Comparison of breakeven point of each design for 20 years life time	80
4.23 Comparison of the greenhouse effect (kg CO ₂ -equivalent) per kilogram of bioethanol for each design	81
4.24 Comparison of the abiotic depletion (kg Sb-equivalent) per kilogram of bioethanol for each design	82
4.25 Comparison of the ozone layer depletion (kg CFC-11-equivalent) per kilogram of bioethanol for each design	82
4.26 Comparison of the human toxicity (kg 1,4-DB-equivalent) per kilogram of bioethanol for each design	83
4.27 Comparison of the flesh water aquatic ecotoxicity (kg 1,4-DB-equivalent) per kilogram of bioethanol for each design	83
4.28 Comparison of the marine aquatic ecotoxicity (kg 1,4-DB-equivalent) per kilogram of bioethanol for each design	84
4.29 Comparison of the terrestrial ecotoxicity (kg 1,4-DB-equivalent) per kilogram of bioethanol for each design	84
4.30 Comparison of the photochemical oxidation (kg C ₂ H ₄) per kilogram of bioethanol for each design	85
4.31 Comparison of the acidification (kg SO ₂ -equivalent) per kilogram of bioethanol for each design	85
4.32 Comparison of the eutrophication (kg PO ₄ -equivalent) per kilogram of bioethanol for each design	86
4.33 Comparison of the improving index for each of alternatives compare to the base case design	87