# CONTENTS

| Declaration by the author   | i           |
|-----------------------------|-------------|
| Certificate from supervisor | ii          |
| Acknowledgement             | iii-iv      |
| Content                     | v-ix        |
| Executive summary           | x-xvii      |
| List of Symbols             | xvii-xx     |
| List of Abbreviations       | xxi-xxii    |
| List of Figures             | xxiv-xxv    |
| List of Tables              | xxvii-xxvii |

## Chapter 1 Introduction

| 1.1 | Background                                   | 1  |
|-----|--|----|
| 1.2 | Use of Bioenergy in Transportation           | 3  |
| 1.3 | Need of Biofuels in India                    | 5  |
| 1.4 | Types of Biorefinery for Biofuels Production | 7  |
| 1.5 | Sustainability Assessment of Biofuels        | 8  |
| 1.6 | Aim and Research Questions                   | 9  |
| 1.7 | Organization of Thesis                       | 11 |

### Chapter 2 Review Literature

| 2.1 | LCA Studies of First Generation (1G) Ethanol          | 15 |
|-----|---|----|
| 2.2 | LCA and LCC Studies of Second Generation (2G) Ethanol | 21 |
| 2.3 | LCA Studies of Rice Straw Utilization Practices       | 30 |

### Chapter 3 Life Cycle Assessment Framework and Methods

| 3.1 | Life Cycl     | e Assessment (LCA) Concept  |                                     |    |
|-----|---------------|---|-------------------------------------|----|
|     | 3.1.1         | Type of L   | CA: Attributional or Consequential  | 33 |
|     | 3.1.2         | Implications of LCA   |                                     | 35 |
| 3.2 | LCA Framework |   | 36                                  |    |
|     | 3.2.1         | Defining (  | Goal and Scope                      | 36 |
|     |               | 3.2.1.1   | Functional Unit (FU)                | 37 |
|     |               | 3.2.1.2   | System Boundary                     | 37 |
|     |               | 3.2.1.3   | Allocation of Environmental Impacts | 38 |
|     | 3.2.2         | Life Cycle  | e Inventory (LCI)                   | 39 |
|     | 3.2.3         | <ul><li>3.2.3 Life Cycle Impact Assessment (LCIA)</li><li>3.2.4 Life Cycle Interpretation</li></ul> |                                     | 40 |
|     | 3.2.4         |   |                                     | 43 |
| 3.3 | General F     | esearch Methodology   |                                     | 44 |

### Chapter 4

### Life Cycle Assessment of First Generation Fuel Ethanol from Sugarcane Molasses in India

| 4.1 | Introduction |             |                                   | 47 |
|-----|--------------|-------------|-----------------------------------|----|
| 4.2 | Aim of St    | tudy        |                                   | 50 |
| 4.3 | Methodol     | ogy         |                                   | 50 |
|     | 4.3.1        | Goal and so | cope                              | 51 |
|     |              | 4.3.1.1     | System boundary                   | 51 |
|     | 4.3.2        | Life Cycle  | Inventory and Process Description | 55 |
|     |              | 4.3.2.1     | Sugarcane Farming                 | 55 |
|     |              | 4.3.2.2     | Sugarcane Transport               | 56 |
|     |              | 4.3.2.3     | Sugar Production                  | 57 |
|     |              | 4.3.2.4     | Molasses Transport                | 58 |
|     |              | 4.3.2.5     | Ethanol Production                | 58 |

|     |                        | 4.3.2.6 Ethanol Transport                  | 59 |
|-----|------------------------|--|----|
|     |                        | 4.3.2.7 Ethanol Blending                   | 60 |
|     | 4.3.3                  | Allocation                                 | 60 |
|     | 4.3.4                  | GHG Emissions and Energy Conversion factor | 60 |
|     | 4.3.5                  | Renewability of ethanol                    | 61 |
| 4.4 | Results and Discussion |  |    |
|     | 4.4.1                  | GHG emissions                              | 62 |
|     | 4.4.2                  | GHG emissions vis-à-vis gasoline           | 65 |
|     | 4.4.3                  | Energy consumption                         | 68 |
|     | 4.4.4                  | Net Energy Ratio (NER)                     |    |
| 4.5 | Environn               | nental benefits of E5 and E10 blends       | 71 |
| 4.6 | Conclusio              | on   | 72 |

### Chapter 5

# Life Cycle Assessment of Second Generation Ethanol from Rice Straw in India

| 5.1 | Introduction |              |  | 74 |
|-----|--------------|--------------|--|----|
| 5.2 | Aim of Study |              |  | 77 |
| 5.3 | Methodology  |              | 78                                     |    |
|     | 5.3.1        | Characteris  | tics of the IOCL 2G Ethanol Technology | 79 |
|     | 5.3.2        | Goal and S   | cope                                   | 79 |
|     |              | 5.3.2.1      | System boundary                        | 80 |
|     | 5.3.3        | Life Cycle   | Inventory and Process Description      | 81 |
|     |              | 5.3.3.1      | Biomass Collection                     | 82 |
|     |              | 5.3.3.2      | Biomass Transport                      | 82 |
|     |              | 5.3.3.3      | Pretreatment                           | 82 |
|     |              | 5.3.3.4      | Enzymatic hydrolysis                   | 84 |
|     |              | 5.3.3.5      | Fermentation                           | 84 |
|     |              | 5.3.3.6      | Distillation and Dehydration           | 84 |
|     |              | 5.3.3.7      | Blending and Distribution              | 85 |
|     |              | 5.3.3.8      | End Use                                | 86 |
|     | 5.3.4        | Allocation   | and System Expansion                   | 86 |
|     | 5.3.5        | Analysis of  | GHG Emissions and Energy Use           | 86 |
| 5.4 | Results and  | d Discussion | l                                      | 88 |
|     | 5.4.1        | GHG Emis     | sions                                  | 89 |
|     | 5.4.2        | GHG emiss    | sions vis-à-vis gasoline               | 91 |
|     | 5.4.3        | Life Cycle   | Energy Use                             | 92 |
|     | 5.4.4        | Net Energy   | Ratio and Net Energy Balance           | 93 |
| 5.5 | Sensitivity  | Analysis     |  | 94 |

| 5.5.1     | Including Agriculture Process in System Boundary  | 94   |
|-----------|---|--|
| 5.5.2     | Enzyme Dosage   | 95   |
| Comparis  | son with Literature Studies   | 96   |
| Conclusio | on and a second s | 99   |
|           | 5.5.2<br>Comparis   | <ul><li>5.5.1 Including Agriculture Process in System Boundary</li><li>5.5.2 Enzyme Dosage</li><li>Comparison with Literature Studies</li><li>Conclusion</li></ul> |

### Chapter 6

### Life Cycle Assessment and Life Cycle Costing of Conventional and Modified Pretreatment Method for Fuel Ethanol Production from Rice Straw in India

| 6.1 | Introduction           |  | 101 |
|-----|------------------------|--|-----|
| 6.2 | Aim of Study           |  | 102 |
| 6.3 | Methodo                | logy   | 103 |
|     | 6.3.1                  | Experimental Design of IOCL Ethanol Technology     | 103 |
|     |                        | 6.3.1.1 Scenarios Description                      | 105 |
|     | 6.3.2                  | Goal and Scope                                     | 106 |
|     | 6.3.3                  | Life Cycle Inventory (LCI) and Process Description | 106 |
|     | 6.3.4                  | Life Cycle Costing (LCC)                           | 109 |
| 6.4 | Results and Discussion |  | 110 |
|     | 6.4.1.                 | Global Warming Potential (GWP)                     | 111 |
|     | 6.4.2                  | Eutrophication Potential (EP)                      | 112 |
|     | 6.4.3                  | Acidification Potential (AP)                       | 114 |
|     | 6.4.4                  | Photochemical Oxidant Creation Potential (POCP)    | 115 |
|     | 6.4.5                  | Life Cycle Costing (LCC)                           | 116 |
| 6.5 | Conclusi               | ion  |     |

### Chapter 7

### Life Cycle Assessment of Rice Straw Utilization Practices in India

| 122 |
|-----|
|     |
| 122 |
| 123 |
| 124 |
| 125 |
| 126 |
| 128 |
| 130 |
| 131 |
| 131 |
|     |

|     | 7.4.2      | Eutrophication Potential (EP)                   | 134 |
|-----|------------|---|-----|
|     | 7.4.3      | Acidification Potential (AP)                    | 136 |
|     | 7.4.4      | Photochemical Oxidant Creation Potential (POCP) | 138 |
| 7.5 | Sensitivit | y Analysis                                      | 139 |
| 7.6 | Compara    | tive LCA of rice straw utilization practices    | 142 |
| 7.7 | Conclusio  | n   | 143 |

## Chapter 8

### **Conclusions and Recommendations**

| 8.1     | Conclusions     | 144 |
|---------|-----------------|-----|
| 8.2     | Recommendations | 146 |
| Refere  | ences           | 148 |
| Short ( | CV              | 169 |
|         |                 |     |