

# BIOFUELS AND BIOENERGY

A Techno-Economic Approach



Edited by

**Baskar Gurunathan**  
**Renganathan Sahadevan**



ELSEVIER

# BIOFUELS AND BIOENERGY

# BIOFUELS AND BIOENERGY

## A Techno-Economic Approach

Edited by

**BASKAR GURUNATHAN**

Department of Biotechnology, St. Joseph's College of Engineering,  
Chennai, Tamil Nadu, India

**RENGANATHAN SAHADEVAN**

Centre for Biotechnology, Anna University, Chennai, Tamil Nadu, India



ELSEVIER

Elsevier

Radarweg 29, PO Box 211, 1000 AE Amsterdam, Netherlands  
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, United Kingdom  
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States

Copyright © 2022 Elsevier Inc. All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: [www.elsevier.com/permissions](http://www.elsevier.com/permissions).

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

MATLAB<sup>®</sup> is a trademark of The MathWorks, Inc. and is used with permission. The MathWorks does not warrant the accuracy of the text or exercises in this book. This book's use or discussion of MATLAB<sup>®</sup> software or related products does not constitute endorsement or sponsorship by The MathWorks of a particular pedagogical approach or particular use of the MATLAB<sup>®</sup> software.

#### Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

ISBN: 978-0-323-90040-9

For Information on all Elsevier publications  
visit our website at <https://www.elsevier.com/books-and-journals>

*Publisher:* Charlotte Cockle  
*Acquisitions Editor:* Peter Adamson  
*Editorial Project Manager:* Michelle Fisher  
*Production Project Manager:* Anitha Sivaraj  
*Cover Designer:* Matthew Lambert

Typeset by MPS Limited, Chennai, India



# Contents

List of contributors

xxv

Preface

xxxiii

## Section I Biorefinery approaches in biofuels and bioenergy production

<b>1. Boundaries and openings of biorefineries towards sustainable biofuel production</b>	<b>3</b>
M. Rajamehala, Renugaa Su, B. Gopalakrishnan, A. Muthu Kumara Pandian, M. Vijay Pradhap Singh and S. Chozhavendhan	
1.1 Introduction	3
1.1.1 Biorefinery	4
1.2 Sources of biorefinery	4
1.2.1 Phase I biorefinery	6
1.2.2 Phase II biorefinery	6
1.2.3 Phase III biorefinery	6
1.3 Classification of biofuels based on biomass	6
1.3.1 First-generation fuels	7
1.3.2 Second-generation fuels	7
1.3.3 Third-generation fuels	7
1.3.4 Fourth-generation fuels	7
1.4 Production methods of biofuel	8
1.5 Pretreatments	8
1.5.1 Mechanical methods	9
1.5.2 Thermochemical methods	9
1.5.3 Chemical pretreatment	10
1.5.4 Biological pretreatment	10
1.6 Production of different biofuels	11
1.6.1 Bioelectricity generation	11
1.7 Production of ethanol and electricity	11
1.8 Production of ethanol, lactic acid, and electricity	12
1.9 Furfural, ethanol and electricity production	12
1.10 Coproduction of butanol and electricity	12
1.11 Production of methanol and electricity	13
1.12 Purification process	13
1.13 Biogas—biomethane production	14

1.14	Applications	15
1.15	Limitations of biorefineries	16
1.16	Future perspectives of biorefineries	16
1.17	Conclusion	16
	References	17
<b>2.</b>	<b>A perspective on the biorefinery approaches for bioenergy production in a circular bioeconomy process</b>	<b>23</b>
	Abiram Karanam Rathankumar, Kongkona Saikia, Senthil Kumar Ponnusamy, Jenet George, Priyanka Saravanan, Anna Shaji, Upasana Mohanty and Vinoth Kumar Vaidyanathan	
2.1	Introduction	23
2.2	Bioenergy	24
2.2.1	Biorefinery	25
2.2.2	Valorization of biomass	28
2.3	Bioeconomy, circular economy, and green economy	31
2.3.1	Circular bioeconomy	32
2.3.2	Biorefinery and circular bioeconomics	33
2.4	Limitations and future perspective of circular bioeconomy	38
2.5	Conclusion	39
	Acknowledgment	40
	References	40
<b>3.</b>	<b>A comprehensive integration of biorefinery concepts for the production of biofuels from lignocellulosic biomass</b>	<b>45</b>
	Kongkona Saikia, Abiram Karanam Rathankumar, Senthil Kumar Ponnusamy, Jenet George, Anna Shaji, Priyanka Saravanan, Upasana Mohanty and Vinoth Kumar Vaidyanathan	
3.1	Introduction	45
3.2	Biomass for biorefinery	46
3.2.1	Algal biorefinery	46
3.2.2	Lignocellulosic biorefinery	48
3.3	Biofuels from lignocellulosic biomass	51
3.4	Strategies for the treatment of lignocellulosic biomass	55
3.4.1	Pretreatment	55
3.4.2	Separate hydrolysis and fermentation	58
3.4.3	Simultaneous saccharification and fermentation	59
3.5	Metabolic engineering approaches for biofuel production	60
3.6	Integrated biorefinery	61
3.7	Constrains and challenges	63
3.8	Economic aspects and future of lignocellulosic biorefinery	63
3.9	Conclusion	64

Acknowledgments	65
References	65
<b>4. Evaluation of activated sludge derived from wastewater treatment process as a potential biorefinery platform</b>	<b>71</b>
Jyotika Thakur and Shyam Kumar Masakapalli	
4.1 Introduction	71
4.2 Activated sludge as a potential resource for fermentative products	72
4.2.1 Analytical techniques to characterize organic valuables in sludge fermentation	73
4.2.2 Organic molecules characterized in sludge fermentation	75
4.3 Activated sludge as refinery for biogases (methane and hydrogen)	76
4.3.1 Physicochemical parameters for activated sludge as biorefinery	76
4.3.2 Biogas yields obtained using sludge fermentation	77
4.3.3 Limitations of sludge bioprocessing and refinements	78
4.4 Activated sludge as a source of other organic by-products (fertilizer, refuse-derived fuel)	79
4.4.1 Reduced sludge for agricultural use	79
4.4.2 Other biorefinery perspectives for reduced sludge	80
4.5 Conclusion	80
Acknowledgments	80
References	81
<b>5. Insights into the impact of biorefineries and sustainable green technologies on circular bioeconomy</b>	<b>85</b>
R. Kheerthivasan, Nadeem Siddiqui, E. Nakkeeran and K. Divakar	
5.1 Introduction	85
5.2 Bioeconomy and circular economy collide in the circular bioeconomy	86
5.3 Impact of biorefinery processes on circular bioeconomy	88
5.4 Product usage strategies for circular bioeconomy	90
5.4.1 Biomimicry and waste biorefinery	91
5.4.2 Metabolic approach	91
5.4.3 Lignocellulosic biorefinery	91
5.4.4 Municipal waste biorefinery	92
5.5 Reusing bio-based high-value products	93
5.6 Effect of biomass utilization on circular bioeconomy	94
5.6.1 Cascading the use of biomass	94
5.6.2 Waste-to-energy technologies	96
5.7 Agriculture management for sustainable circular bioeconomy	97
5.8 Industrial and environmental policy for promoting circular bioeconomy	97
5.9 Conclusion	99
References	99

## Section II Biofuels and bioenergy production - I

<b>6. Fermentation technology for ethanol production: current trends and challenges</b>	<b>105</b>
Mani Jayakumar, Selvakumar Kuppusamy Vaithilingam, Natchimuthu Karmegam, Kaleab Bizuneh Gebeyehu, Maria Susai Boobalan and Baskar Gurunathan	
6.1 Introduction	105
6.2 Lignocellulosic biomass	105
6.3 The electronic structure chemistry of cellulose, hemicellulose, and lignin	108
6.4 Pretreatment of lignocellulosic biomass	110
6.5 Fermentation technology	111
6.5.1 Separate hydrolysis and fermentation	111
6.5.2 Simultaneous saccharification and fermentation	117
6.6 Ethanol production using native microbes	117
6.6.1 C5 sugar fermentative microbes	118
6.6.2 C6 sugar fermentative microbes	119
6.7 Fermentation technology for ethanol production using recombinant engineered microbes	119
6.7.1 Yeast ( <i>Saccharomyces cerevisiae</i> )	120
6.7.2 <i>Zymomonas mobilis</i>	120
6.7.3 <i>Escherichia coli</i>	121
6.8 Trends, challenges, and future prospects in the bioethanol production	121
6.8.1 Trends	121
6.8.2 Challenges and prospects	122
6.9 Conclusion	123
References	123
<b>7. Improved enzymatic hydrolysis of lignocellulosic waste biomass: most essential stage to develop cost-effective second-generation biofuel production</b>	<b>133</b>
Pinaki Dey, Geetika Gupta, Jayato Nayak and Kevin Joseph Dilip	
7.1 Introduction	133
7.2 Enzymatic saccharification of lignocellulosic feedstocks	135
7.2.1 Different modes of enzymatic saccharification and their technical aspects	139
7.3 Factors influences in efficient enzymatic saccharification of lignocellulosic biomass	141
7.3.1 Ideal pretreatment of biomass	141
7.3.2 Utilization of potent enzymes, produced from waste biomasses and high-yield microbes	144
7.3.3 Reaction conditions influencing enzymatic hydrolysis process	148
7.4 Reusability of cellulase enzyme to develop cost-effective enzymatic saccharification process	152



7.5	Economic aspects and future prospective of enzymatic saccharification-based lignocellulosic biofuel production	156
7.6	Conclusion	157
	References	158
<b>8.</b>	<b>Advances and sustainable conversion of waste lignocellulosic biomass into biofuels</b>	<b>167</b>
	J. Iyyappan, Baskar Gurunathan, M. Gopinath, A. Vaishnavi, S. Prathiba, V. Kanishka, K. Gomathi and V. Dhithya	
8.1	Introduction	167
8.2	Biofuel: a sustainable fuel for future	168
8.3	Lignocellulose: a potential substrate for the biofuel product	169
8.4	Pretreatment methods for lignocellulose biomass	171
8.4.1	Physical methods	172
8.4.2	Mechanical pretreatment methods	173
8.4.3	Irradiation pretreatment method	173
8.4.4	Pyrolysis	174
8.4.5	Chemical methods	175
8.4.6	Biological pretreatment methods	177
8.4.7	Microbial pretreatment method	178
8.5	Sources of lignocellulose biomass	178
8.5.1	Agricultural biomass	178
8.5.2	Forestry biomass	181
8.5.3	Industrial and municipal biomass	184
8.5.4	Wasteland biomass	187
8.6	Analysis	190
8.6.1	Fourier transform infrared spectroscopy/X-ray	190
8.7	Potential microbial strains involved in biofuel productions	190
8.8	Fermentation methods for biofuel production	194
8.8.1	Separated hydrolysis and fermentation	194
8.8.2	Simultaneous saccharification and fermentation	195
8.9	Reactor configuration	195
8.10	Future perspectives	196
8.11	Challenges	198
8.12	Conclusion	199
	References	200
<b>9.</b>	<b>Lignocellulosic biomass as an alternate source for next-generation biofuel</b>	<b>207</b>
	M. Rajamehala, A. Kaviprabha, A. Muthu Kumara Pandian, M. Vijay Pradhap Singh, S. Karthikadevi, B. Gopalakrishnan and S. Chozhavendhan	
9.1	Introduction	207

9.2	Raw materials	209
9.2.1	Wheat	209
9.2.2	Corn	209
9.2.3	Sugarcane	210
9.2.4	Wood/straw dust	211
9.3	Lignocellulosic material	211
9.3.1	Composition of lignocellulosic feedstocks	211
9.4	Process for converting the lignocellulose to biofuels	212
9.4.1	Biological process	213
9.4.2	Thermochemical process	217
9.5	Conclusion	218
	References	218

**10. Process intensification in biobutanol production 223**

Kailas L. Wasewar

10.1	Introduction	223
10.2	Biobutanol	225
10.2.1	Need of biobutanol	225
10.2.2	Characteristics of biobutanol	226
10.2.3	Applications of butanol	227
10.3	Production of biobutanol	228
10.3.1	Preface for biobutanol production	228
10.3.2	History of biobutanol production	229
10.3.3	Categories of biobutanol	231
10.3.4	Microorganism for biobutanol production	231
10.3.5	Challenges in biobutanol production	232
10.4	Process intensification	232
10.5	Process intensification in production of biobutanol	233
10.5.1	Bioreactors	234
10.5.2	Continuous biofilm fixed bed reactor	235
10.5.3	Membrane methods	236
10.5.4	Distillation methods	242
10.5.5	Fermentation with gas stripping	242
10.5.6	Liquid–liquid extraction methods	245
10.5.7	Adsorption methods	246
10.5.8	Hybrid methods	248
10.5.9	Other methods	250
10.6	Conclusion	253
	References	253

<b>11. Production of cellulosic butanol by clostridial fermentation: a superior alternative renewable liquid fuel</b>	<b>263</b>
Gobinath Rajagopalan and Chandraraj Krishnan	
11.1 Introduction	263
11.2 Production of butanol by <i>Clostridium</i> sp	264
11.2.1 ABE fermentation	264
11.2.2 IBE fermentation	266
11.3 Factors affecting butanol production	268
11.4 Enhancement of ABE fermentation	269
11.4.1 Coculture of <i>Clostridium</i> sp	269
11.4.2 Metabolic engineering	272
11.5 Butanol production from LCB	273
11.5.1 Separate hydrolysis and fermentation	273
11.5.2 Consolidated bioprocessing of LCB	277
11.6 Technoeconomic analysis	279
11.7 Conclusion	280
References	280
<b>12. Biobutanol separation using ionic liquids as a green solvent</b>	<b>291</b>
Kailas L. Wasewar	
12.1 Introduction	291
12.2 Butanol	292
12.2.1 Background	292
12.2.2 Characteristics	292
12.2.3 Applications	293
12.2.4 Production	293
12.2.5 Separation	296
12.3 Liquid–liquid extraction and ionic liquids	297
12.3.1 Separation	297
12.3.2 Liquid–liquid extraction	297
12.3.3 Ionic liquids	298
12.4 Butanol separation by ionic liquids	300
12.4.1 Imidazolium-based ionic liquids	302
12.4.2 Phosphonium-based ionic liquids	305
12.4.3 Piperidinium-based ionic liquids	306
12.4.4 Pyrrolidinium-based ionic liquids	306
12.4.5 Morpholinium-based ionic liquids	306
12.4.6 Ammonium-based ionic liquids	307
12.4.7 Supported ionic liquid membrane	307
12.4.8 Perstraction using ionic liquids	310

12.5	Toxicity and biocompatibility of ionic liquids	310
12.5.1	Biocompatibility	310
12.5.2	Toxicity	311
12.6	Recovery and reuse of ionic liquids	312
12.7	Future perspectives	313
12.8	Conclusion	317
	References	318

### **13. Synergistic prospects of microalgae after wastewater treatment to be used for biofuel production** **323**

Louis Anto Nirmal, Sholinghur Asuri Bhakthochidan, Ravichandran Vishal, Veeraraghavan Babulu Roshini and Samuel Jacob

13.1	Introduction	323
13.2	Appropriate selection methods for effective biofuel production	324
13.2.1	Potential microalgae for biofuel production through wastewater treatment	324
13.2.2	Selection of appropriate media for enhanced microalgal biomass and lipid yield	325
13.2.3	Selection of wastewater for microalgal growth	326
13.2.4	Selection of wastewater pretreatment	327
13.2.5	Free cell versus immobilized cell	327
13.3	Types of microalgae cultivation	328
13.3.1	High rate algal ponds	328
13.3.2	Photobioreactor	329
13.3.3	Hybrid system	330
13.3.4	Microalgae turf scrubber	331
13.4	Harvesting microalgal biomass	331
13.4.1	Chemical extraction	331
13.4.2	Mechanical extraction	332
13.4.3	Electrical extraction	332
13.4.4	Biological method of extraction	332
13.5	Biofuel production from wastewater using microalgae	333
13.5.1	Biodiesel	333
13.5.2	Bioethanol and biohydrogen	335
13.5.3	Syngas	336
13.5.4	Biomethane	337
13.5.5	Jet fuel	337
13.6	Greenhouse gas mitigation	338
13.7	Future perspectives	339
13.8	Conclusion	341
	References	341

<b>14. Concurrent reduction of CO<sub>2</sub> and generation of biofuels by electrified microbial systems—concepts and perspectives</b>	<b>347</b>
Bhargavi Gunturu, Adam Shahul Hameed and Renganathan Sahadevan	
14.1 Introduction	347
14.1.1 Electrode and possible effects on microbial electrosynthesis	354
14.1.2 Membrane configurations	360
14.2 Bacterial electrotophs	360
14.3 Mechanism of electron uptake	363
14.3.1 Indirect extracellular electron transfer or mediator-dependent transfer	364
14.3.2 Direct extracellular electron transfer or mediator-free transfer	365
14.4 Carbon dioxide reduction and biofuels generation	365
14.5 Challenges and future prospects	371
14.6 Conclusion	372
References	372

## **Section III Biofuels and bioenergy production—II**

<b>15. Challenges and opportunities in large-scale production of biodiesel</b>	<b>385</b>
Umaiyambika Neduvel Annal, Arunodhaya Natarajan, Baskar Gurunathan, Vijay Mani and Renganathan Sahadevan	
15.1 Introduction	385
15.2 Assessment from small-scale to large-scale production	387
15.2.1 Supply chain and logistics	387
15.2.2 Storage of oil seed	388
15.3 Commercial-scale production of triglycerides	389
15.3.1 Source of triglycerides	389
15.3.2 Large scale oil production	389
15.3.3 Vegetable oil refining process	390
15.3.4 Degumming	391
15.3.5 Deacidification process	391
15.3.6 Bleaching	392
15.3.7 Deodorization process	392
15.4 Large-scale production structure of biodiesel plant	393
15.4.1 Refining process for biodiesel production	394
15.4.2 Esterification process	394
15.4.3 Transesterification process	394
15.4.4 Pumps and pipelines used	395
15.4.5 Reactors used	396
15.4.6 Product separation	397

15.4.7	Neutralization	398
15.4.8	Methanol recovery	398
15.4.9	Biodiesel purification	398
15.4.10	Biodiesel drying	399
15.4.11	Recovery of methanol	399
15.5	Glycerol purification	400
15.5.1	Free fatty acid treatment	400
15.6	Wastewater treatment	401
15.6.1	Generation of wastewater	401
15.6.2	Significance of wastewater treatment method	401
15.6.3	Physical methods	403
15.6.4	Electrochemical method	403
15.6.5	Biological methods	404
15.7	Cost analysis of wastewater treatment	404
15.7.1	Economic analysis of biodiesel production	404
15.8	Conclusion	405
	References	406
<b>16.</b>	<b>Lipid-derived biofuel: production methodologies</b>	<b>409</b>
	Umaiymbika Neduvel Annal, Arunodhaya Natarajan, Baskar Gurunathan and Renganathan Sahadevan	
16.1	Introduction	409
16.2	Properties of biodiesel	410
16.3	Biodiesel production methodologies	410
16.3.1	Direct use and blending	410
16.3.2	Microemulsion	411
16.3.3	Pyrolysis	413
16.4	Transesterification process	416
16.4.1	Parameters affecting transesterification process	417
16.4.2	Types of transesterification process	419
16.5	Overview of production methods	430
16.6	Conclusion	431
	References	431
<b>17.</b>	<b>Interesterification reaction of vegetable oil and alkyl acetate as alternative route for glycerol-free biodiesel synthesis</b>	<b>435</b>
	Ratna Dewi Kusumaningtyas, Indah Purnamasari, Ririn Mahmudati and Haniif Prasetiawan	
17.1	Introduction	435
17.2	Biodiesel	436
17.3	Interesterification reaction	439

17.4	Kinetic model of interesterification reaction	440
17.5	Case study: kinetic study on the biodiesel synthesis from <i>Jatropha</i> ( <i>Jatropha curcas</i> L.) with methyl acetate in the presence of sodium methoxide catalyst	442
17.5.1	Methods	442
17.5.2	Kinetic model	443
17.5.3	Characterization of <i>Jatropha</i> oil	443
17.5.4	Effect of catalyst concentration	444
17.5.5	Effect of <i>Jatropha</i> oil to methyl acetate molar ratio	445
17.5.6	Effect of reaction time and temperature	447
17.5.7	Kinetic study	448
17.6	Conclusion	450
	Acknowledgment	450
	References	450

## **18. Recent advances of lipase-catalyzed greener production of biodiesel in organic reaction media: economic and sustainable viewpoint** **453**

Kirtikumar C. Badgujar, Vivek C. Badgujar and Bhalchandra M. Bhanage

18.1	Introduction	453
18.2	Recent literature survey of lipase-catalyzed synthesis of biodiesel	454
18.3	Reaction parameters	461
18.3.1	Biocatalyst screening	461
18.3.2	Effect of oil-to-alcohol mole ratio	463
18.3.3	Effect of stepwise addition of alcohol	463
18.3.4	Effect of solvent and cosolvent	466
18.3.5	Effect of temperature	467
18.3.6	Effect of water content	469
18.3.7	Effect of biocatalyst amount	471
18.3.8	Effect of mass transfer	473
18.3.9	Effect of adsorbent	473
18.3.10	Effect alcohol chain length	473
18.3.11	Effect of feedstock (waste or fresh oils) from various sources	474
18.3.12	Effect of recycle	474
18.4	Economic and sustainable viewpoint	475
18.4.1	Catalyst lipase and immobilization	475
18.4.2	Use of waste feedstock	475
18.4.3	Processing parameters and optimization	476
18.4.4	Scale-up synthesis	476
18.4.5	Greenness of the process	477
18.5	Conclusion	477
	References	477

<b>19. Efficient utilization of seed biomass and its by-product for the biodiesel production</b>	<b>483</b>
Praveena Nagarajan, Baskar Gurunathan, Sivakumar Pandian, Ilango Karuppasamy, Geethalakshmi Ramakrishnan and Renganathan Sahadevan	
19.1 Introduction	483
19.2 Second-generation feedstock for biodiesel production	484
19.2.1 Advantages of nonedible oils	484
19.3 Problems in the exploitation of nonedible oils	485
19.4 Deoiled seed meal after oil extraction	485
19.4.1 Sulfonation	486
19.4.2 Carbonization followed by sulfonation	486
19.4.3 Hydrothermal carbonization	486
19.4.4 Pyrolyzation followed by sulfonation	486
19.5 Seed cake as a catalyst for esterification process	486
19.6 Factors influencing seed cake catalyst preparation	487
19.6.1 Reusability of catalyst	490
19.7 Characterization of catalyst	491
19.8 Conclusion	491
References	492
<b>20. Catalytic pyrolysis for upgrading of biooil obtained from biomass</b>	<b>495</b>
Nidhi Agnihotri and Monoj Kumar Mondal	
20.1 Introduction	495
20.2 Catalytic fast pyrolysis of biomass	496
20.2.1 Advantages of catalytic pyrolysis	498
20.3 Commercial-scale pyrolysis plant	498
20.4 Types of catalysts used in pyrolysis	499
20.4.1 Zeolites	499
20.4.2 Mesoporous catalyst	500
20.5 Chemical reactions in catalytic fast pyrolysis	501
20.5.1 Deoxygenation	501
20.5.2 Cracking	501
20.5.3 Dehydration	501
20.5.4 Decarboxylation	502
20.6 Reactors for catalytic pyrolysis	502
20.7 Process parameters	504
20.7.1 Temperature	505
20.7.2 Ratio of biomass to catalyst	505
20.7.3 Catalyst contact time	505
20.7.4 Vapor residence time	506



20.8	Challenges and recommendations	506
20.9	Future perspectives	507
20.10	Conclusion	507
	Acknowledgments	508
	References	508
<b>21.</b>	<b>Recent trends in the pyrolysis and gasification of lignocellulosic biomass</b>	<b>511</b>
	Vinoj Kurian, Manjot Gill, Bijay Dhakal and Amit Kumar	
21.1	Introduction	511
21.1.1	Background	511
21.1.2	Potential feedstocks for pyrolysis and gasification	513
21.1.3	Pretreatment of lignocellulosic biomass	517
21.2	Pyrolysis	518
21.2.1	Types of pyrolysis	519
21.2.2	Reactor configuration	521
21.2.3	Factors affecting pyrolysis products	527
21.2.4	Recent developments in pyrolysis	530
21.2.5	Current status and challenges of pyrolysis	532
21.3	Gasification	533
21.3.1	Gasification theory	533
21.3.2	Gasifier types	536
21.3.3	Current status and challenges of gasification	541
21.4	Future of pyrolysis and gasification	542
21.4.1	Biomass-based hydrogen	542
21.4.2	Bioethanol	545
21.5	Conclusion	546
	References	547
<b>22.</b>	<b>Experimental investigation of performance of bio diesel with different blends in diesel engine</b>	<b>553</b>
	P. Saranya, R. Anantharaj, D. Gnana Prakash and M. Vichitra	
22.1	Introduction	553
22.1.1	Need for alternative green fuel	553
22.1.2	Cashew nut shell liquid	553
22.1.3	Cardanol	554
22.2	Experimental section	555
22.2.1	Materials	555
22.2.2	Measurements	555
22.2.3	Blending of auxiliaries with cardanol	556
22.2.4	Engine performance analysis	558

22.3	Results and discussion	560
22.3.1	Density of pure components	560
22.3.2	Performance and emission characteristics of alternative green fuel	560
22.4	Conclusion	566
	References	567

## **Section IV Technoeconomic and environmental impact analysis of biofuels and bioenergy**

### **23. Technoeconomic evaluation of 2G ethanol production with coproducts from rice straw 571**

Panneerselvam Ranganathan

23.1	Introduction	571
23.2	Process description of rice straw to ethanol and coproducts	576
23.2.1	Pretreatment of rice straw	577
23.2.2	Enzymatic hydrolysis	577
23.2.3	Glucose (C6) fermentation	577
23.2.4	Xylose (C5) fermentation	578
23.2.5	Coproducts from rice straw	578
23.3	Process design	578
23.3.1	Various cases	578
23.3.2	Simulation methodology	582
23.4	Results and discussion	583
23.4.1	Material flow	583
23.4.2	Economic analysis	585
23.4.3	Sensitivity analysis	586
23.5	Future perspective	587
23.6	Conclusion	587
	References	588

### **24. Technoeconomic analysis of biodiesel production using noncatalytic transesterification 591**

E. Yuvanashree, Renganathan Sahadevan and Baskar Gurunathan

24.1	Introduction	591
24.2	Characteristics of supercritical methanol	593
24.3	Reaction kinetics of transesterification	594
24.4	Upshots of operating parameters on biodiesel using SCM	595
24.4.1	Temperature	595
24.4.2	Pressure	596
24.4.3	Alcohol/oil ratio	597

24.4.4	Feedstock handling	597
24.5	Technoeconomic analysis of SCM method	597
24.5.1	Case study	598
24.5.2	Process results	598
24.5.3	Economic review	598
24.6	Conclusion	599
	References	599
<b>25.</b>	<b>Techno-economic analysis of biodiesel production from nonedible biooil using catalytic transesterification</b>	<b>601</b>
	Naveenkumar Rajendran, Ashok Pandey, Edgard Gnansounou, Baskar Gurunathan and Jeehoon Han	
25.1	Introduction	601
25.2	Nonedible source for biodiesel production	602
25.2.1	Gossypium	602
25.2.2	Jatropha curcas	602
25.2.3	Simmondsia chinensis	603
25.2.4	Milletia pinnata	603
25.2.5	Linum usitatissimum	603
25.2.6	Madhuca longifolia	603
25.2.7	Azadirachta indica	604
25.2.8	Hevea brasiliensis	604
25.2.9	Nicotiana tabacum	604
25.2.10	Callophyllum inophyllum	604
25.3	Catalyst for biodiesel production	605
25.3.1	Homogeneous Catalyst	605
25.3.2	Heterogeneous Catalyst	606
25.4	Techno-economic analysis	611
25.4.1	Steps involved in techno-economic analysis	613
25.4.2	Economic factors	613
25.5	Techno-economic analysis of biodiesel production	615
25.6	Conclusion	618
	Reference	619
<b>26.</b>	<b>Technoeconomic analysis of biofuel production from marine algae</b>	<b>627</b>
	G. Kalavathy, Ashok Pandey, Edgard Gnansounou and Baskar Gurunathan	
26.1	Introduction	627
26.2	Macroalgae production	629
26.2.1	Cultivation	630
26.2.2	Harvesting	631
26.2.3	Postharvesting	632

26.3	Extraction of oil from macroalgae for biodiesel production	633
26.3.1	Pretreatment of algal biomass	633
26.3.2	Soxhlet extraction	633
26.3.3	Factors affecting extraction of algal oil	634
26.4	Production of biodiesel	636
26.4.1	Transesterification of algal oil	636
26.5	Production of biogas from macroalgae	639
26.5.1	Anaerobic digestion	640
26.6	Production of bioethanol from marine macroalgae	640
26.7	Technoeconomic analysis	642
26.7.1	Hatchery and grow-out systems	642
26.7.2	Drying systems	643
26.7.3	Transportation systems	643
26.7.4	Algal oil extraction systems	643
26.7.5	Transesterification of algal oil	644
26.7.6	Fermentation	644
26.7.7	Technoeconomic analysis of biofuel from macroalgae	644
26.8	Conclusion	646
	References	646
<b>27.</b>	<b>Techno-economic assessment of biofuel production using thermochemical pathways</b>	<b>653</b>
	Prasad Mandade and Yogesh M. Nimdeo	
27.1	Introduction	653
27.2	Thermochemical pathways of biofuel production	656
27.2.1	Torrefaction	657
27.2.2	Hydrothermal liquefaction	658
27.2.3	Pyrolysis	659
27.2.4	Gasification	660
27.3	Techno-economic assessment of biofuels using thermochemical methods	660
27.3.1	Methodological framework of techno-economic assessment	660
27.3.2	Overview of the techno-economic assessment studies of biofuel production using thermo-chemical pathways	663
27.4	Challenges, progress, opportunities, and future perspectives	666
27.5	Conclusion	668
	References	668
<b>28.</b>	<b>Modeling and technoeconomic analysis of biogas production from waste food</b>	<b>673</b>
	G. Srinivas, P. Ramesh, G.B. Radhika and T. Srinivas	
28.1	Introduction	673

28.2	Materials and methods	675
28.3	Technoeconomic analysis	676
28.4	Results and discussion	677
28.5	Economic analysis results	683
28.6	Conclusion	683
	References	684

## **29. Techno-economic and environmental impact analysis of biofuels produced from microalgal biomass 687**

C. Nagendranatha Reddy, Y. Vineetha, A. Priyanka, A. Shalini, Bishwambhar Mishra, Y. Rajasri and V. Swapna

29.1	Introduction	687
29.2	Technological assessment	690
29.2.1	Influential factors for biodiesel production	691
29.2.2	Algae cultivation	691
29.2.3	Biomass pretreatment and extraction	693
29.2.4	Harvesting of algal culture	693
29.2.5	Extraction	693
29.2.6	Transesterification	695
29.2.7	Scale-up	695
29.3	Economic assessment	696
29.3.1	Cost analysis	697
29.3.2	Techno-economic analysis	697
29.4	Environmental impact assessment	700
29.4.1	Microalgal biomass	701
29.5	Major challenges associated with biofuels production from microalgal biomass	706
29.6	Conclusions	707
	References	708

## **30. Computer-aided environmental and technoeconomic analyses as tools for designing biorefineries under the circular bioeconomy approach 713**

Samir Meramo

30.1	Introduction	713
30.2	Circular bioeconomy framework towards biorefinery design	715
30.3	Computer-aided environmental analysis of biorefineries	717
30.4	Computer-aided technoeconomic analysis of biorefineries	720
30.5	Case study for the production of ethanol and succinic acid under circular economy	723
30.6	Environmental assessment of ethanol and succinic acid production under circular bioeconomy	728

30.7	Technoeconomic assessment of ethanol and succinic acid production under circular bioeconomy	731
30.8	Conclusions	734
	References	735
<b>31.</b>	<b>Environmental impact analysis of biofuels and bioenergy: a globalperspective</b>	<b>739</b>
	J. Iyyappan, Baskar Gurunathan, M. Gopinath, A. Vaishnavi, S. Prathiba, V. Kanishka, K. Gomathi and V. Dhithya	
31.1	Introduction	739
31.2	Biofuel: a sustainable fuel for future	740
31.3	Bioenergy: a sustainable fuel for future	740
31.4	Resource availability for biofuel production	741
31.5	Impact of biomass on environment	744
31.6	Impact of combustion efficiency in environment	745
31.7	Impact of biofuel production on biodiversity	746
31.8	Environmental impacts on biomass pretreatment	747
31.9	Managing ecosystems and its services	749
31.10	Regulations related to environmental sustainability	749
31.11	Impact of biofuel production on water quality	751
31.12	Conclusion	752
	References	752
<b>32.</b>	<b>Environmental impacts of biofuels and their blends: a case study on waste vegetable oil-derived biofuel blends</b>	<b>755</b>
	Pritam Dey and Srimanta Ray	
32.1	Introduction	755
32.2	Environmental impacts of biofuels	756
32.2.1	Life cycle assessment methodology	757
32.2.2	Environmental impact categories	757
32.3	Environmental impacts of waste vegetable oil-based biofuels: a case study	759
32.3.1	Methods	759
32.3.2	Physical properties of various test fuels	760
32.3.3	Engine performance and emission analysis	761
32.3.4	Environmental impacts of various waste vegetable oil-based biofuels	762
32.4	Conclusion	768
	Acknowledgments	769
	References	769

<b>33. Solid biofuel production, environmental impact, and technoeconomic analysis</b>	<b>771</b>
Elsa Cherian, Lakshmi Mohan and K.A. Anju	
33.1 Introduction	771
33.2 Importance of solid fuel	772
33.3 Types of solid biofuels	772
33.3.1 Wood-based fuel	773
33.3.2 Coal and coke	774
33.3.3 Peat	775
33.4 Processes for the usage of solid biofuel	775
33.4.1 Anaerobic digestion	776
33.4.2 Saccharification and fermentation	776
33.4.3 Torrefaction	776
33.4.4 Liquefaction	777
33.4.5 Gasification	777
33.4.6 Combustion	778
33.5 Environmental impact of solid biofuels	778
33.6 Technoeconomic analysis of solid biofuel	781
33.7 Conclusions	784
References	784
<i>Index</i>	787

# List of contributors

## **Nidhi Agnihotri**

Department of Chemical Engineering and Technology, Indian Institute of Technology (Banaras Hindu University), Varanasi, Uttar Pradesh, India

## **R. Anantharaj**

Department of Chemical Engineering, Sri Sivasubramaniya Nadar College of Engineering, Chennai, Tamil Nadu, India

## **K.A. Anju**

Department of Food Technology, SAINTGITS College of Engineering, Kottayam, Kerala, India

## **Umaiyambika Neduvel Annal**

Biofuels Lab, Centre for Biotechnology, Anna University, Chennai, Tamil Nadu, India

## **Kirtikumar C. Badgajar**

Department of Chemistry, Institute of Chemical Technology, Mumbai, Maharashtra, India;  
Department of Chemistry, SIES College of Arts, Science & Commerce, Mumbai, Maharashtra, India

## **Vivek C. Badgajar**

Department of Chemistry, Pratap College of Arts, Science & Commerce, Amalner, Maharashtra, India

## **Sholinghur Asuri Bhakthochidan**

Department of Biotechnology, School of Bioengineering, SRM Institute of Science and Technology, Chennai, Tamil Nadu, India

## **Bhalchandra M. Bhanage**

Department of Chemistry, Institute of Chemical Technology, Mumbai, Maharashtra, India

## **Maria Susai Boobalan**

Department of Chemistry, College of Natural and Computational Sciences, Haramaya University, Dire Dawa, Oromiya Regional State, Ethiopia

## **Elsa Cherian**

Department of Food Technology, SAINTGITS College of Engineering, Kottayam, Kerala, India

## **S. Chozhavendhan**

Department of Biotechnology, VSB Engineering College, Karur, Tamil Nadu, India

## **Pinaki Dey**

Department of Biotechnology, Karunya Institute of Technology and Sciences, Coimbatore, Tamil Nadu, India

## **Pritam Dey**

Department of Chemical Engineering, National Institute of Technology Agartala, Jirania, Tripura, India



**Bijay Dhakal**

Department of Mechanical Engineering, University of Alberta, Edmonton, AB, Canada

**V. Dhithya**

Department of Biotechnology, Vel Tech High Tech Dr. Rangarajan Dr. Sakunthala Engineering College, Chennai, Tamil Nadu, India

**Kevin Joseph Dilip**

Department of Life Sciences, National Dong Hwa University, Taipei, Taiwan, China

**K. Divakar**

Department of Biotechnology, Sri Venkateswara College of Engineering, Sriperumbudur, Tamil Nadu, India

**Kaleab Bizuneh Gebeyehu**

Chemical Engineering, Haramaya Institute of Technology, Haramaya University, Dire Dawa, Oromiya Regional State, Ethiopia

**Jenet George**

Integrated Bioprocessing Laboratory, Department of Biotechnology, School of Bioengineering, SRM Institute of Science and Technology, Chennai, Tamil Nadu, India

**Manjot Gill**

Department of Mechanical Engineering, University of Alberta, Edmonton, AB, Canada

**D. Gnana Prakash**

Department of Chemical Engineering, Sri Sivasubramaniya Nadar College of Engineering, Chennai, Tamil Nadu, India

**Edgard Gnansounou**

Bioenergy and Energy Planning Research Group, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

**K. Gomathi**

Department of Biotechnology, Vel Tech High Tech Dr. Rangarajan Dr. Sakunthala Engineering College, Chennai, Tamil Nadu, India

**B. Gopalakrishnan**

Department of Chemical Engineering, Annamalai University, Chidambaram, Tamil Nadu, India

**M. Gopinath**

Department of Biotechnology, Vel Tech High Tech Dr. Rangarajan Dr. Sakunthala Engineering College, Chennai, Tamil Nadu, India

**Bhargavi Gunturu**

Bionanomaterials laboratory, Centre for Biotechnology, Anna University, Chennai, Tamil Nadu, India

**Geetika Gupta**

Department of Biotechnology, Thapar Institute of Engineering and Technology, Patiala, Punjab, India

**Baskar Gurunathan**

Department of Biotechnology, St. Joseph's College of Engineering, Chennai, Tamil Nadu, India

**Adam Shahul Hameed**

Biofuels laboratory, Centre for Biotechnology, Anna University, Chennai, Tamil Nadu, India

**Jeehoon Han**

School of Semiconductor and Chemical Engineering, Jeonbuk National University, Jeonju, Republic of Korea

**J. Iyyappan**

Department of Biotechnology, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences (SIMATS), Chennai, Tamil Nadu, India

**Samuel Jacob**

Department of Biotechnology, School of Bioengineering, SRM Institute of Science and Technology, Chennai, Tamil Nadu, India

**Mani Jayakumar**

Chemical Engineering, Haramaya Institute of Technology, Haramaya University, Dire Dawa, Oromiya Regional State, Ethiopia

**G. Kalavathy**

Department of Biotechnology, St. Joseph's College of Engineering, Chennai, Tamil Nadu, India

**V. Kanishka**

Department of Biotechnology, Vel Tech High Tech Dr. Rangarajan Dr. Sakunthala Engineering College, Chennai, Tamil Nadu, India

**Natchimuthu Karmegam**

Department of Botany, Government Arts College (Autonomous), Salem, Tamil Nadu, India

**S. Karthikadevi**

Department of Biotechnology, Vivekanandha College of Engineering for Women, Tiruchengode, Tamil Nadu, India

**Ilango Karuppasamy**

Department of Electrical and Electronics Engineering, Amrita Vishwa Vidyapeetham, Coimbatore, Tamil Nadu, India

**A. Kaviprabha**

Department of Biotechnology, Vivekanandha College of Engineering for Women, Tiruchengode, Tamil Nadu, India

**R. Kheerthivasan**

Department of Biotechnology, Sri Venkateswara College of Engineering, Sriperumbudur, Tamil Nadu, India

**Chandraraj Krishnan**

Department of Biotechnology, Indian Institute of Technology Madras, Chennai, Tamil Nadu, India

**Amit Kumar**

Department of Mechanical Engineering, University of Alberta, Edmonton, AB, Canada

**Selvakumar Kuppusamy Vaithilingam**

School of Chemical and Bio Engineering, Dire Dawa University Institute of Technology, Dire Dawa University, Dire Dawa, Ethiopia

**Vinoj Kurian**

Department of Mechanical Engineering, University of Alberta, Edmonton, AB, Canada

**Ratna Dewi Kusumaningtyas**

Chemical Engineering Department, Faculty of Engineering, Universitas Negeri Semarang, Kampus UNNES, Semarang, Indonesia

**Ririn Mahmudati**

Chemical Engineering Department, Faculty of Engineering, Universitas Negeri Semarang, Kampus UNNES, Semarang, Indonesia

**Prasad Mandade**

Bioenergy and Energy Planning Research Group, EPFL, Lausanne, Switzerland

**Vijay Mani**

Department of Chemical Engineering, Annamalai University, Chidambaram, Tamil Nadu, India

**Shyam Kumar Masakapalli**

BioX Center, School of Basic Sciences, Indian Institute of Technology Mandi, Kamand, Himachal Pradesh, India

**Samir Meramo**

Sustainable Innovation Office, Novo Nordisk Foundation Center for Biosustainability, Technical University of Denmark, Lyngby, Denmark

**Bishwambhar Mishra**

Department of Biotechnology, Chaitanya Bharathi Institute of Technology, Hyderabad, Telangana, India

**Lakshmi Mohan**

Department of Food Technology, SAINTGITS College of Engineering, Kottayam, Kerala, India

**Upasana Mohanty**

Integrated Bioprocessing Laboratory, Department of Biotechnology, School of Bioengineering, SRM Institute of Science and Technology, Chennai, Tamil Nadu, India

**Monoj Kumar Mondal**

Department of Chemical Engineering and Technology, Indian Institute of Technology (Banaras Hindu University), Varanasi, Uttar Pradesh, India

**A. Muthu Kumara Pandian**

Department of Biotechnology, Vivekanandha College of Engineering for Women, Tiruchengode, Tamil Nadu, India

**Praveena Nagarajan**

Centre for Biotechnology, Anna University, Chennai, Tamil Nadu, India

**E. Nakkeeran**

Department of Biotechnology, Sri Venkateswara College of Engineering, Sriperumbudur, Tamil Nadu, India

**Arunodhaya Natarajan**

Department of Petroleum Engineering, Rajiv Gandhi College of Engineering, Chennai, Tamil Nadu, India

**Jayato Nayak**

Department of Chemical Engineering, Kalasalingam Academy of Research and Education (Deemed to be University), Krishnankoil, Tamil Nadu, India

**Yogesh M. Nimdeo**

Department of Chemical Engineering, Indian Institute of Technology Jammu, Jammu, India

**Louis Anto Nirmal**

Department of Biotechnology, School of Bioengineering, SRM Institute of Science and Technology, Chennai, Tamil Nadu, India

**Ashok Pandey**

CSIR-Indian Institute of Toxicology Research, Lucknow, Uttar Pradesh, India

**Sivakumar Pandian**

School of Petroleum Technology, Pandit Deedayal Energy University, Gandhinagar, Gujarat, India

**Senthil Kumar Ponnusamy**

Department of Chemical Engineering, Sri Sivasubramaniya Nadar College of Engineering, Chennai, Tamil Nadu, India

**Haniif Prasetiawan**

Chemical Engineering Department, Faculty of Engineering, Universitas Negeri Semarang, Kampus UNNES, Semarang, Indonesia

**S. Prathiba**

Department of Biotechnology, Vel Tech High Tech Dr. Rangarajan Dr. Sakunthala Engineering College, Chennai, Tamil Nadu, India

**A. Priyanka**

Department of Biotechnology, Chaitanya Bharathi Institute of Technology, Hyderabad, Telangana, India

**Indah Purnamasari**

Chemical Engineering Department, Faculty of Engineering, Universitas Negeri Semarang, Kampus UNNES, Semarang, Indonesia

**G.B. Radhika**

Department of Chemical Engineering, B V Raju Institute of Technology, Narsapur, Medak Dist, Telangana, India

**Gobinath Rajagopalan**

Industrial Biotechnology Laboratory, Faculty of Life Sciences and Biotechnology, South Asian University (SAU), New Delhi, India

**M. Rajamehala**

Department of Biotechnology, Vivekanandha College of Engineering for Women, Tiruchengode, Tamil Nadu, India

**Y. Rajasri**

Department of Biotechnology, Chaitanya Bharathi Institute of Technology, Hyderabad, Telangana, India

**Naveenkumar Rajendran**

Department of Biotechnology, St. Joseph's College of Engineering, Chennai, Tamil Nadu, India; School of Chemical Engineering, Jeonbuk National University, Jeonju, Republic of Korea

**Geethalakshmi Ramakrishnan**

Centre for Biotechnology, Anna University, Chennai, Tamil Nadu, India

**P. Ramesh**

Department of Chemical Engineering, B V Raju Institute of Technology, Narsapur, Medak Dist, Telangana, India

**Panneerselvam Ranganathan**

Department of Chemical Engineering, National Institute of Technology Calicut, Kozhikode, Kerala, India

**Abiram Karanam Rathankumar**

Integrated Bioprocessing Laboratory, Department of Biotechnology, School of Bioengineering, SRM Institute of Science and Technology, Chennai, Tamil Nadu, India

**Srimanta Ray**

Department of Chemical Engineering, National Institute of Technology Agartala, Jirania, Tripura, India

**C. Nagendranatha Reddy**

Department of Biotechnology, Chaitanya Bharathi Institute of Technology, Hyderabad, Telangana, India

**Veeraraghavan Babulu Roshini**

Department of Biotechnology, School of Bioengineering, SRM Institute of Science and Technology, Chennai, Tamil Nadu, India

**Renganathan Sahadevan**

Centre for Biotechnology, Anna University, Chennai, Tamil Nadu, India

**Kongkona Saikia**

Integrated Bioprocessing Laboratory, Department of Biotechnology, School of Bioengineering, SRM Institute of Science and Technology, Chennai, Tamil Nadu, India

**P. Saranya**

Department of Chemical Engineering, Sri Sivasubramaniya Nadar College of Engineering, Chennai, Tamil Nadu, India

**Priyanka Saravanan**

Integrated Bioprocessing Laboratory, Department of Biotechnology, School of Bioengineering, SRM Institute of Science and Technology, Chennai, Tamil Nadu, India

**Anna Shaji**

Integrated Bioprocessing Laboratory, Department of Biotechnology, School of Bioengineering, SRM Institute of Science and Technology, Chennai, Tamil Nadu, India

**A. Shalini**

Department of Biotechnology, Chaitanya Bharathi Institute of Technology, Hyderabad, Telangana, India

**Nadeem Siddiqui**

Department of Biotechnology, Koneru Lakshmaiah Education Foundation, Guntur, Andhra Pradesh, India

**G. Srinivas**

Department of Chemical Engineering, B V Raju Institute of Technology, Narsapur, Medak Dist, Telangana, India

**T. Srinivas**

Department of Chemical Engineering, B V Raju Institute of Technology, Narsapur, Medak Dist, Telangana, India

**Renugaa Su**

Department of Biotechnology, Vivekanandha College of Engineering for Women, Tiruchengode, Tamil Nadu, India

**V. Swapna**

Department of Chemical Engineering, Chaitanya Bharathi Institute of Technology, Hyderabad, Telangana, India

**Jyotika Thakur**

BioX Center, School of Basic Sciences, Indian Institute of Technology Mandi, Kamand, Himachal Pradesh, India

**Vinoth Kumar Vaidyanathan**

Integrated Bioprocessing Laboratory, Department of Biotechnology, School of Bioengineering, SRM Institute of Science and Technology, Chennai, Tamil Nadu, India

**A. Vaishnavi**

Department of Biotechnology, Vel Tech High Tech Dr. Rangarajan Dr. Sakunthala Engineering College, Chennai, Tamil Nadu, India

**M. Vichitra**

Department of Chemical Engineering, Sri Sivasubramaniya Nadar College of Engineering, Chennai, Tamil Nadu, India

**M. Vijay Pradhap Singh**

Department of Biotechnology, Vivekanandha College of Engineering for Women, Tiruchengode, Tamil Nadu, India

**Y. Vineetha**

Department of Biotechnology, Chaitanya Bharathi Institute of Technology, Hyderabad, Telangana, India

**Ravichandran Vishal**

Department of Biotechnology, School of Bioengineering, SRM Institute of Science and Technology, Chennai, Tamil Nadu, India

**Kailas L. Wasewar**

Advance Separation and Analytical Laboratory (ASAL), Department of Chemical Engineering,  
Visvesvaraya National Institute of Technology (VNIT), Nagpur, Maharashtra, India

**E. Yuvanashree**

Biofuels Lab, Centre for Biotechnology, Anna University, Chennai, Tamil Nadu, India

## Preface

Biorefineries utilize renewable sources for the production of various biofuels using integrated approaches. Currently, biorefinery approaches are facing many technical challenges. It is important to refine biorefinery concepts to overcome these challenges and make commercially viable biorefineries. This book *Biofuels and Bioenergy: A Techno-Economic Approach* covers the latest developments in biorefinery approaches for the production of various biofuels and bioenergy by the utilization of various solid and liquid renewable feedstocks. This book also covers biorefinery approaches for circular bioeconomy, techno-economic analysis of biofuels production, environmental impact analysis of biofuels, microbial electrosynthesis of biofuels, and performance of biodiesel in a diesel engine. This book provides comprehensive information on biorefinery approaches for biofuels and bioenergy under four sections comprising 33 chapters as detailed here.

Section I focused on biorefinery approaches in biofuels and bioenergy production. This section covers various chapters such as boundaries and openings of biorefineries toward sustainable biofuel production, a perspective on the biorefinery approaches for bioenergy production in a circular bioeconomy process, a comprehensive integration of biorefinery concepts for the production of biofuels from lignocellulosic biomass, evaluation of activated sludge derived from wastewater treatment process as a potential biorefinery platform, and insights into the impact of biorefineries and sustainable green technologies on circular bioeconomy.

Section II comprising nine chapters focused on fermentation technology for ethanol production: current trends and challenges, improved enzymatic hydrolysis of lignocellulosic waste biomass: most essential stage to develop cost-effective bio-fuel production, advances and sustainable conversion of waste lignocellulosic biomass into biofuels, lignocellulosic biomass as an alternate source for next-generation biofuel, process intensification of biobutanol production, production of n-butanol by clostridial fermentation: a superior alternative renewable liquid fuel, biobutanol separation using ionic liquids as a green solvent, synergistic prospects of microalgae in wastewater treatment and third-generation biofuel production and concurrent reduction of carbon dioxide and generation of biofuels by electrified microbial systems—concepts and perspectives.

Section III comprising eight chapters focused on biofuels and bioenergy production such as challenges and opportunities in large-scale production of biodiesel, lipid-derived biofuel: production methodologies, interesterification reaction of vegetable oil and alkyl acetate as alternative route for glycerol-free biodiesel synthesis, recent



advances of lipase catalyzed greener production of biodiesel in organic reaction media: economic and sustainable viewpoint, efficient utilization of biomass-derived heterogeneous catalyst for biodiesel production, catalytic pyrolysis for upgrading of bio-oil obtained from biomass, recent trends in pyrolysis and gasification of lignocellulosic biomass and experimental investigation of performance of biodiesel with different blends in a diesel engine.

Section IV is mainly about the techno-economic and environmental impact analysis of biofuels and bioenergy. This section includes the chapters such as techno-economic evaluation of 2G ethanol production with co-products from rice straw, techno-economic analysis for production of biodiesel using noncatalytic transesterification, techno-economic analysis of biodiesel production from nonedible biooil using catalytic transesterification, techno-economic analysis of biofuels production from marine algae, techno-economic assessment of biofuel production using thermochemical pathways, modeling and techno-economic analysis of biogas production from waste food, biofuels production from algal biomass: environmental impact and techno-economic analysis, computer-aided environmental and techno-economic analyses as tools for development of biorefineries under the circular bioeconomy approach, environmental impact analysis of biofuels and bioenergy—a global perspective, environmental impacts of biofuels and their blends: a case study on waste vegetable oil-derived biofuel blends and solid biofuels production, environmental impact and techno-economic analysis.

*Biofuels and Bioenergy: A Techno-Economic Approach* is a hands-on reference for faculty members, researchers, scientists, and practicing engineers working on various fields of bioenergy, biorefinery, and biofuels' production. This book is a good source of information addressing industrial problems relevant to undergraduate, postgraduate, and research students under different academic departments such as biotechnology, chemical, energy, and environmental engineering in various universities and academic institutions.

**Baskar Gurunathan  
Renganathan Sahadevan**

## CHAPTER 17

# Interesterification reaction of vegetable oil and alkyl acetate as alternative route for glycerol-free biodiesel synthesis

**Ratna Dewi Kusumaningtyas, Indah Purnamasari, Ririn Mahmudati and  
Haniif Prasetiawan**

Chemical Engineering Department, Faculty of Engineering, Universitas Negeri Semarang, Kampus UNNES, Semarang, Indonesia

### 17.1 Introduction

The world population growth and industrial development has led to the increasing of the global energy needs. To date, fossil energy, which includes petroleum, coal, and natural gas, has fulfilled around 80% of the world energy demand. In particular, petroleum shares approximately 90% of the fuel consumption in the transportation sector. Fossil energy dominates the total energy supply (TES) source as reported by the International Energy Agency (IEA) (IEA, 2020). Utilization of fossil fuel as major energy resources has embarked on several dares related to the oil reserves decimation and environmental issues. The data provided by the U.S. Energy Information Administration indicates that the petroleum and other liquid fuel consumption throughout 2019–22 tends to be higher than its production (EIA, 2020a). This unbalanced condition is predicted to be severer in the future due to the growth of population, transportation, and industrial sectors. In fact, the worse condition happens in some countries with significant declining in oil reserves.

At the same time, fossil fuel is under pressure to respond to the climate change issue. Concerning the environmental aspects, combustion of fossil fuel is stated as the major contributor of the greenhouse gases' (such as CO<sub>2</sub>, NO<sub>x</sub>) emission to the atmosphere, causing the increasing temperature of the planet and an extreme climate change during the last few years. Therefore the energy transition from fossil-based fuel to carbon-neutral or zero carbon energy resources is important for carbon reduction in energy sector. This is also in line with the policy of the United Nation which has set up the Sustainable Development Goal (SDG) 7 in terms of affordable and clean energy by 2030 (Asadikia et al., 2021). According to the Paris Climate Agreement 2015, it is

also expected to confine the global temperature increase to 1.5°C, to lessen the negative effect of climate change, and to achieve net-zero emission of energy utilization by 2050 (Kato and Kurosawa, 2019; Lopez et al., 2021). Furthermore, the new paradigm of the energy sustainability established by the World Energy Council comprises the three main attributes, which is called Trilemma: energy security, energy equity, and environmental sustainability of energy system (World Energy Council, 2020). In this context, energy also has enduring mission to reach a better lives for people (Gadonneix et al., 2020).

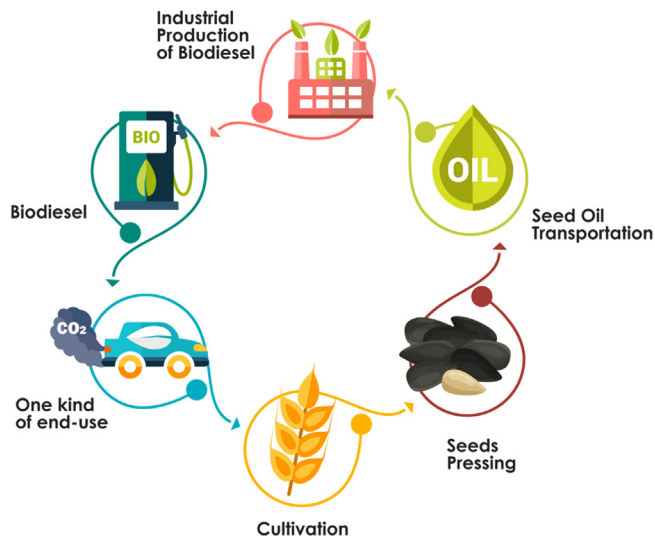
Based on the SDG 7 and Trilemma concept, enhancement in energy security and sustainability should proceed concurrently. One of the key to provide affordable energy with low environmental negative impact is deploying renewable energy as substitute to the fossil-based energy (Bertheau, 2020; Gielen et al., 2019). Renewable energy, especially with zero carbon or neutral carbon characteristic, has great potential to contribute in lowering the greenhouse gases' emission. Innovation in its process technology likewise could decrease the production cost. Yet, it expected that renewable energy can afford 8% of the global energy consumption. Enhancing the portion of renewable energy in the world's energy consumption is one among the three main targets of SDG 7 for 2030 (Santika et al., 2020). Therefore it is essential to work on the renewable energy development, particularly which is applied for transportation as the biggest CO<sub>2</sub> emitter. Based on IEA projection for change in the global energy mix 2019–40, it is indicated that bioenergy is among the important renewable energy (CAPP, 2020).

Biodiesel is one of bioenergy. It is derived from vegetable oil which can be utilized as substitute for petroleum diesel. It is regarded as carbon neutral since the vegetable oils as common feedstock of biodiesel are obtained from plants, in which plants take up carbon dioxide (CO<sub>2</sub>) from the air for photosynthesis. The absorption of CO<sub>2</sub> by these plants thus counterbalances the CO<sub>2</sub> released during the production and combustion of biodiesel as presented in Fig. 17.1 (EIA, 2020b). Therefore substituting fossil fuel with biodiesel is beneficial for decarbonizing the energy system.

## 17.2 Biodiesel

Biodiesel is classified as biomass-based diesel fuels, which can be used as substitute of petroleum diesel. Utilization of biodiesel as alternative diesel fuel is strategic since diesel engine is extensively used in many sectors, for instance agriculture, transportation, and industry (Ma et al., 2021; Ogunkunle and Ahmed, 2019). Compared to fossil diesel, biodiesel shows many advantages, namely, nontoxic, biodegradable, safer due to its higher flash point (less inflammable), and more environmentally friendly. Biodiesel also holds higher cetane number better fuel lubricity, superior ignition performance, and higher combustion efficiency. Additionally, combustion of biodiesel releases lower

## BIODIESEL LIFE CYCLE



**Figure 17.1** Biodiesel as carbon-neutral renewable energy source.

emission in the form of particulates, CO, SO<sub>2</sub>, hydrocarbon, as well as other air toxics and pollutants (Kusumaningtyas et al., 2014; Ma et al., 2021; Traviss and Treadwell, 2018). And again, owing to its carbon-neutral characteristic, utilization of biodiesel as fossil diesel substitute will contribute to reduced climate change and global warming.

Biodiesel is usually applied as diesel engine fuel in form of biodiesel–petroleum diesel blending in various ratios, such as 2%, 5%, 7%, 10%, 20%, or 30%. The higher ratio or even pure biodiesel can be utilized, as well (Ogunkunle and Ahmed, 2019; Widjanarko et al., 2020). Biodiesel has been used extensively in many countries as part of the government policy on renewable energy, such as B20 in the United States under the Energy Policy Act of 1992 (AFDC, 2008), B30 in Indonesia under MEMR Regulation Number 12/2015 (Santika et al., 2020), B15 in Malaysia, and B10 in Thailand (Zulqarnain et al., 2020).

Biodiesel, which is also currently known as fatty acid methyl ester (FAME), is commonly produced using vegetable oils as raw material. In fact, vegetable-based bio-fuel application has long been known since Rudolf Diesel employed peanut oil as the fuel for the diesel engine and demonstrated it at the world fair in Paris in 1900 (Ma and Hanna, 1999; Ogunkunle and Ahmed, 2019). But, then, the popularity of this biofuel was decreasing because of the fossil-fuel booming in the early 20th century. When the issue on the oil reserve exhaustion and energy crisis emerged in 1980s, biodiesel was gaining attention for the second time as alternative energy to the fossil diesel fuel. However, vegetable oil cannot be directly applied for today's diesel engine due

to its exceptionally high viscosity. To fulfill the specification which suits the current diesel engine, vegetable oil should be processed to reduce its viscosity. The product is nowadays named biodiesel. There are several methods to convert vegetable oils into biodiesel, among others:

1. Pyrolysis
2. Microemulsification
3. Dilution
4. Two-step preparation: hydrolysis and methyl esterification
5. Transesterification
6. Interesterification

Pyrolysis is thermal breakdown of organic materials in the absence of oxygen. It can be direct or catalytic thermal cracking. Triglyceride pyrolysis results in hydrocarbons and oxygenated organic compounds, such as alkanes, alkenes, alkadienes, aromatic, and carboxylic acid. The liquid fraction of the pyrolysis product is alike diesel fuel. The heating value is comparable, but the values of the cetane number, flash point, viscosity, and pour point are lower than petroleum diesel (Maher and Bressler, 2007; Ogunkunle and Ahmed, 2019). Microemulsification is preparing a microemulsion of two immiscible liquids by adding surfactant to attain a thermodynamically stable dispersion. It is also termed as cosolvent blending. This method can decrease the viscosity of the oil (Ma and Hanna, 1999; Ogunkunle and Ahmed, 2019; Pereira et al., 2016). Dilution is blending vegetable oil with diesel fuel at a certain ratio to reduce its viscosity (Nguyen et al., 2010; Ogunkunle and Ahmed, 2019). On the other hand, Kusdiana and Saka (2004) have reported a method named two-step preparation of biodiesel at supercritical condition. The process involves hydrolysis of triglycerides to produce fatty acid and glycerol, followed by esterification of fatty acid with supercritical methanol to yield in FAME.

The most common method for biodiesel synthesis at the present time is through the alkaline-catalyzed transesterification of triglycerides of vegetable oils with methanol. The mechanism of transesterification comprises three steps: (1) conversion of triglyceride to 1 mole of FAME and diglyceride, (2) conversion of diglyceride to 1 mole of FAME and monoglyceride, and (3) conversion of monoglyceride to 1 mole of FAME and glycerol (Schuchardt et al., 1998).

The shortage of transesterification reaction is that this reaction produces glycerol as by-product and needs to be separated from the main product (biodiesel). Low purity of glycerol is less valuable, hence it is considered as a waste. To avoid the formation of glycerol side product, methanol can be replaced by methyl acetate or ethyl acetate (Kashyap et al., 2019). The reaction between vegetable oils with alkyl acetate, known as interesterification, will produce biodiesel and triacetin instead of glycerol. It is not necessary to separate triacetin from biodiesel product since triacetin has characteristic as fuel additive, which can improve biodiesel combustion performance form (Dhawan et al., 2020).

### 17.3 Interesterification reaction

The classical transesterification reaction to produce biodiesel generates glycerol as a by-product. This fact is unfavorable since it needs a set of separation process to purify biodiesel from glycerol, which consequently increases the production cost. On the other hand, the abundant product of crude glycerol causes the declining price of glycerol in the market (Kusumaningtyas et al., 2016; Lazdovica and Kampars, 2020). Therefore development of the glycerol-free process for biodiesel synthesis has grabbed a significant attention.

One attracting way to eliminate the formation of biodiesel is by using alkyl acetate as reactant instead of methanol. By substituting methanol with methyl or ethyl acetate, glycerol will not be yielded as by-product. As a substitute, the reaction between triglyceride and alkyl acetate will result in biodiesel and triacetin. The alternative route of biodiesel production using alkyl acetate as the acyl acceptor is called interesterification. This reaction can be catalyzed using enzyme, classical homogeneous catalyst such as sodium or potassium methoxide, heterogeneous catalyst, and in the absence of catalyst using supercritical condition. Metal alkoxide catalyst is among the most effective catalyst for interesterification reaction since it can result in high yield in a short time and mild condition (Lazdovica and Kampars, 2020).

In the interesterification reaction, it is unnecessary to separate triacetin, which is formed during the reaction since triacetin can be blended with biodiesel as fuel additive (Casas et al., 2011; Maddikeri et al., 2014). As fuel additive, triacetin acts to improve the cetane number of the biodiesel. As the impact, it reduces the smoke emission and knocking of engine. Besides, the addition of triacetin will promote the cold properties of biodiesel. Biodiesel can be formulated with triacetin up to 10% or 20% (Lazdovica and Kampars, 2020; Maddikeri et al., 2014; Mufrodi et al., 2014).

The reaction equation of interesterification of 1 molecule of triglyceride with 3 molecules of methyl acetate results in 3 molecules of FAMES (biodiesel) and 1 molecule of triacetin. The reaction mechanism shows that interesterification reaction is complex reaction consisting of three consecutive steps. Based on its reaction mechanism, interesterification reaction is identical to a combination of two transesterification reactions (Casas et al., 2013). In this work, interesterification between triglycerides of *Jatropha* oil and methyl acetate was conducted to produce biodiesel. Catalyst used in this process was sodium methoxide ( $\text{NaOCH}_3$ ). Kinetic study was also performed in this investigation.

There are many different seed oils that can be utilized as raw material for biodiesel production. The selection of the vegetable oil depends on several factors, for instance: the locally available feedstocks, price, oil composition, technical aspect, etc. In the European Union, biodiesel is mostly prepared from rapeseed oil (Dutta, 2019; Van Duren et al., 2015). Meanwhile, soybean oil is the most dominant biodiesel feedstock

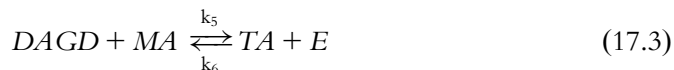
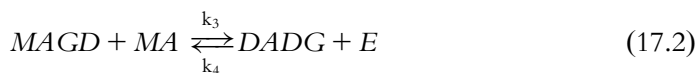
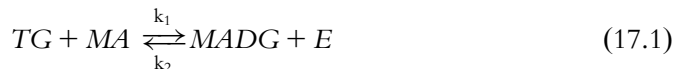
in the United States (Chen et al., 2018). Waste cooking oil is also a potential feedstock in various countries (Fangfang et al., 2021). In tropical and coastal countries such as Indonesia and Malaysia, palm and coconut oil are widely applied as raw materials for biodiesel production. *Jatropha curcas* oil is also popular in Asian countries, such as India, Malaysia, and Indonesia (Anwar, 2021; Hamzah et al., 2020; Siregar et al., 2015).

Utilization of *Jatropha curcas* Linn. oil is promising since it is a nonedible oil. Hence, its utilization as bioenergy crop will not compete with the food demand (Kusumaningtyas et al., 2014). *Jatropha* seed has high oil content between 63.16% and 66.4%, which is higher than the oil content of palm kernel and soybean (Hamzah et al., 2020). In addition, the cetane number of *Jatropha* biodiesel is reported to be 57, which is comparable to diesel fuel and higher than palm biodiesel. The Life Cycle Assessment (LCA) has revealed that *Jatropha* biodiesel demonstrated the higher reduction value of CO<sub>2</sub> release from combustion than palm biodiesel (Siregar et al., 2015).

## 17.4 Kinetic model of interesterification reaction

Kinetic study is urgent for obtaining the kinetic parameters, which is required for the process equipment design and scaling up. However, study on the kinetics of triglyceride interesterification for biodiesel production is not widely found in literature (Brondani et al., 2020). Most findings focus on the kinetics of enzymatic interesterification, and some other discuss about the kinetics of the interesterification at supercritical condition. Kinetic analysis of the interesterification reaction using classical metal alkoxides catalyst in mild condition has not been extensively investigated. In spite of this, some research reported the compatibility of the homogeneous irreversible second-order model for this reaction (Casas et al., 2011; Teixeira et al., 2016).

Basically, interesterification consist of three sequential reversible reactions that can be described through Eqs. (17.1)–(17.3). Furthermore, the overall reaction is written in Eq. (17.4) (Casas et al., 2011):



Overall reaction:



Reaction rate of each compound can be written as follow [Eqs. (17.5)–(17.10)]:

$$d\frac{[TG]}{dt} = -k_1[TG][MA] + k_2[MADG][E] - k_7[TG][MA]^3 + k_8[TA][E]^3 \quad (17.5)$$

$$d\frac{[MADG]}{dt} = k_1[TG][MA] - k_2[MADG][E] - k_3[MADG][MA] + k_4[DAMG][E] \quad (17.6)$$

$$d\frac{[DAMG]}{dt} = k_3[MADG][MA] - k_4[DAMG][E] - k_5[DAMG][MA] + k_6[TA][E] \quad (17.7)$$

$$d\frac{[E]}{dt} = k_1[TG][MA] - k_2[MADG][E] + k_3[MADG][MA] - k_4[DAMG][E] \\ + k_5[DAMG][MA] - k_6[TA][E] + k_7[TG][MA]^3 - k_8[TA][E]^3 \quad (17.8)$$

$$d\frac{[MA]}{dt} = -d\frac{[E]}{dt} \quad (17.9)$$

$$d\frac{[TA]}{dt} = k_5[DAMG][MA] - k_6[TA][E] + k_7[TG][MA]^3 - k_8[TA][E]^3 \quad (17.10)$$

where  $TG$  = triglycerides,  $MADG$  = monoacetin diglyceride,  $DAMG$  = diacetin mono-glyceride, and  $E$  = FAME (biodiesel).

Generally, the value of the reaction rate constant on the secondary group is slightly greater than that of the primary group. Since the difference constant values are not exceedingly significant, it can be assumed that the reaction, which comprises three steps occurs simultaneously. Subsequently, the overall reaction in Eq. (17.4) can be rewritten as Eq. (17.11):



The reaction rate equation can be formulated as follows [Eq. (17.12)]:

$$d\frac{[TG]}{dt} = -k_1'[TG][MA]^3 + k_2'[TA][E]^3 \quad (17.12)$$

where  $k_1'$  = reaction rate constant for the forward reaction and  $k_2'$  = reaction rate constant for the reverse reaction.

Reaction rate constant in general is defined using Arrhenius function [Eq. (17.13)]:

$$k(T) = Ae^{-E/RT} \quad (17.13)$$



where  $k(T)$  = reaction rate constant,  $A$  = frequency/preexponential factor,  $E$  = activation energy (mol/J),  $R$  = ideal gas constant (8314 J/K.mol), and  $T$  = reaction temperature (K).

The units for  $k(T)$  and  $A$  depend on the reaction order, namely L/mol.min and  $\text{min}^{-1}$  for the first- and second-order reactions, respectively.

Casas et al. (2011) suggested a kinetic model of irreversible interesterification of triglycerides with methyl acetate so as to Eq. (17.12) can be simplified. Once the excessive methyl acetate is employed in the reaction system, it can be assumed that forward reaction in Eq. (17.12) obeys a pseudo-first-order reaction, and the reverse reaction follows the second-order reaction law. However, when far excess methyl acetate is used in the reaction, the  $k$  value of the reverse reaction can be disregarded and supposed to be zero. For this reason, the interesterification reaction can be considered an irreversible reaction. Thus Eq. (17.12) can be simplified into a second-order irreversible reaction kinetic model as indicated in Eq. (17.14):

$$-\frac{dC_{TG}}{dt} = r_{TG} = k' \cdot C_{TG}^2 \quad (17.14)$$

The kinetic model obtained is then presented in Eq. (17.15):

$$\frac{1}{C_{TG}} = k' \cdot t + \frac{1}{C_{TG_0}} \quad (17.15)$$

The value of  $k'$  is affected by the catalyst concentration.

Plotting of  $\frac{1}{C_{TG}}$  against  $t$  will form a linear line, denoting that the model fits the experimental data. where  $C_{TG}$  = molar concentration of triglycerides (mol/L),  $C_{TG_0}$  = initial concentration of triglycerides (mol/L),  $t$  = reaction time (min),  $r_{TG}$  = reaction rate of triglycerides (mol/L.min), and  $k'$  = reaction rate constant (L/mol.min).

## 17.5 Case study: kinetic study on the biodiesel synthesis from *Jatropha* (*Jatropha curcas* L.) with methyl acetate in the presence of sodium methoxide catalyst

In this case, *Jatropha* oil was obtained from PT. *Jatropha* Green Energi, Kudus, Jawa Tengah, Indonesia. Experimental study and kinetic reaction rate were inspected in this study. The experiment was conducted through interesterification reaction of *J. curcas* L. with methyl acetate in the presence of  $\text{NaOCH}_3$  catalyst. Consecutively, kinetic factor and activation energy of interesterification reaction were obtained from the proposed kinetic model.

### 17.5.1 Methods

There are two main stages in this case, which are neutralization of crude *Jatropha* oil and interesterification of neutralized *Jatropha* oil. The physical and chemical properties

of *Jatropha* oil such as density, viscosity, acid value, and acidity were analyzed before and after neutralization process.

Purification or neutralization of *Jatropha* oil was intended to remove the free fatty acid and avoid the gumming process in the transesterification reaction. Two hundred milliliters of crude *Jatropha* oil was prepared in a three-necked flask. Sodium carbonate ( $\text{Na}_2\text{CO}_3$ ) was dissolved in a water with combined a mixing and heating process. Saturated  $\text{Na}_2\text{CO}_3$  was then filtered to remove the unwanted solid and undissolved  $\text{Na}_2\text{CO}_3$  powder. The oil was heated to  $90^\circ\text{C}$ , and once it reached the neutralization temperature ( $90^\circ\text{C}$ ), saturated  $\text{Na}_2\text{CO}_3$  was injected into the oil at a low flow rate. Continuous mixing was conducted for 1 h and the solution was then separated to remove the produced soap from the oil.

$\text{NaOCH}_3$  was mixed with methyl acetate in a three-necked flask accompanied with magnetic stirrer, and the mixture was then heated to operating temperature. Purified *Jatropha* oil was prepared in a different apparatus and also heated to the same temperature with catalyst mixture. Once it reached the required temperature, the *Jatropha* oil was then poured into the previous three-necked flask, which contains catalyst and methyl acetate.

In this transesterification reaction, the catalyst concentration was varied to 0.25%, 0.5%, 0.75%, and 1%, oil to molar ratio was varied to 1:6, 1:9, 1:12, and 1:15, while the reaction time was varied to  $40^\circ\text{C}$ ,  $50^\circ\text{C}$ , and  $60^\circ\text{C}$ . Transesterification was conducted for 8 h and the samples were taken periodically. The samples were then analyzed its composition by using gas chromatography–mass spectrometry (GC-MS).

### 17.5.2 Kinetic model

Triglycerides concentration from GC-MS analysis was converted into the reaction conversion. The kinetic model was then solved by using Eqs. (17.14) and (17.15), which are the proposed by Casas et al. (2011). The differential equation was solved by using Runge–Kutta method. Experimental data and the calculated triglyceride concentration were compared and calculated its sum square of error (SSE). Kinetic rate constant was determined once it reached the minimum SSE.

Kinetic factor and the energy activation were obtained by using Arrhenius equation as shown in Eq. (17.16).

$$k(T) = Ae^{-E/RT} \quad (17.16)$$

where  $k(T)$  is the reaction rate constant (L/mol.min),  $A$  is the frequency/preexponential factor (L/mol.min),  $E$  is the energy activation (mol/J),  $R$  is the ideal gas constant (8314 J/K.mol), and  $T$  is the reaction temperature (K).

### 17.5.3 Characterization of *Jatropha* oil

Characteristics of *Jatropha* oil before and after neutralization process are demonstrated in Table 17.1. The characterization consists of oil density, viscosity, molecular weight,

**Table 17.1** Physical and chemical properties of Jatropha oil.

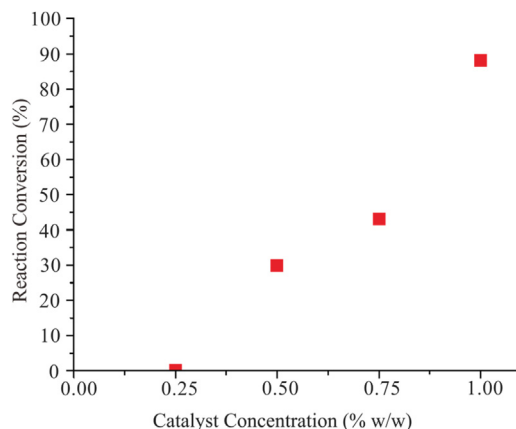
Variable	Standard	Before	After
Density (g/mL)	0.85–0.89	0.965	0.956
Viscosity (mm <sup>2</sup> /s)	2.3–6.0	37.83	40.39
Acid value (mg KOH/g oil)	Max 0.80	16.157	0.926
Acidity (%)	Max 0.5	8.12	0.465

acid value, and acidity. According to [Table 17.1](#), it can be seen that neutralization process has successfully decreased all the parameters compared to the crude Jatropha oil. However, most of the parameter values are still above the required standard for diesel engine. It can be concluded that this crude oil cannot be directly used as diesel engine. Several problems that might appear when crude oil with the current physical and chemical properties is used as diesel engine are engine failure, increasing the engine weariness ([Pristiyani, 2015](#)), power loss engine ([Mittlebach and Remschmidt, 2004](#)), corrosion, and create deposit on the engine ([Ferrari et al., 2011](#)). Since the acidity value is already dropped to 0.465%, this purified Jatropha oil can be used for the next process to produce the methyl ester.

#### 17.5.4 Effect of catalyst concentration

In this case, the concentration of NaOCH<sub>3</sub> catalyst was varied into 0.25%, 0.5%, 0.75%, and 0.1% w/w, while the other variables were remaining constant. The oil to methyl acetate molar ratio was 1:6, reaction temperature was set at 50°C, and the reaction time was 4 h. NaOCH<sub>3</sub> catalyst was chosen since it contains less water compared to sodium hydroxide (KOH) ([Ma and Hanna, 1999](#)). Based on this operating condition, the effect of catalyst concentration on the triglyceride conversion is shown in [Fig. 17.2](#).

The result shows that higher catalyst concentration also increases the number of converted triglyceride into methyl ester. This was caused by the increasing number of available active sites to promote the reaction ([Masduki et al., 2013](#)). With the increasing number of active sites, it also reduces the energy activation and increases the reaction rate of triglyceride into methyl ester ([Rasyid, 2010](#)). Reduction on the energy activation creates more collision between the reactant particles, which can increase the reaction rate. In this case, the highest conversion was 88.1% obtained by using catalyst concentration of 1%. [Maddikeri et al. \(2014\)](#) in their study also reported that the optimum catalyst concentration for the interesterification of cooking oil was 1%. Higher catalyst concentration did not affect the conversion; on the other hand, it increases the catalyst recovery cost. On the previous study, [Pristiyani \(2015\)](#) used KOH for interesterification of used cooking oil. The results showed that the highest conversion obtained was 13.79. It can be concluded that NaOCH<sub>3</sub> is more effective as an interesterification catalyst compared to KOH.



**Figure 17.2** Effect of catalyst concentration on the triglyceride conversion.

**Table 17.2** Methyl ester chemical compounds at the catalyst concentration of 1% w/w.

No.	Retention time, min	Area %	Chemical compound
1	43.056	0.79	Oleic acid
2	43.795	0.36	Linoleic acid
3	45.770	4.54	Methyl ester
4	49.907	10.74	Palmitic acid
5	54.825	3.14	Methyl ester
6	55.249	3.40	Mono-oleic acid
7	59.475	0.22	Methyl ester

Table 17.2 shows the chemical compounds of methyl ester by using 1% w/w of  $\text{NaOCH}_3$  catalyst. It can be seen that at the current catalyst concentration and operating condition, triacetin was not found on the compounds of methyl ester although it has a quite high triglyceride conversion. [Sustere and Kampars \(2015\)](#) on the previous studies found that the optimum results were obtained by using catalyst to oil ratio of 0.15 with methyl acetate to oil molar ratio of 36. The catalyst used was tert-butoxide, and the product composition was 73.2% of methyl ester and 16.6% of triacetin. Since in this case the methyl ester to oil molar ratio was only 6:1, it might be the main reason triacetin was not found in the product.

### 17.5.5 Effect of *Jatropha* oil to methyl acetate molar ratio

According to the stoichiometry of interesterification reaction, 3 moles of methyl acetate is reacted with 1 mole of triglyceride. Since it is a reversible reaction, excess methyl acetate is needed to shift the reaction towards the product side ([Maddikeri et al., 2014](#)). Effect of the oil to methyl acetate molar ratio to triglyceride conversion

was studied at 1:6, 1:9, 1:12, and 1:15. The reaction was conducted at reaction temperature of 50°C, catalyst concentration of 0.5% w/w, and reaction time of 4 h. Fig. 17.3 shows the effect of oil to methyl acetate molar ratio to the triglyceride conversion.

It can be seen that the conversion of triglyceride into methyl ester is decreasing along with the increasing of oil to methyl acetate molar ratio. Huang and Akoh (1996) also reported the same trend line on their study, and yield of transesterification product between triolein and caprylic acid ethyl ester was not increasing with the increasing reactant molar ratio. Moreover, excess amount of methyl ester might produce biodiesel with high viscosity and became another issue on the product separation. Reduction on the reaction conversion was caused by the low amount of triglyceride concentration, furthermore this excessive dissolution inflicted a slower reaction process. In reversible reactions such as interesterification, excess ethyl acetate might slide the equilibrium to the backward reaction, which can reduce the yield of biodiesel and triacetin (Komintarachat et al., 2015). In this case, the highest conversion was obtained at oil to methyl acetate molar ratio of 1:6 with a conversion of 29.76%. Freedman et al. (1984) previously studied the effect of molar ratio on the sunflower oil methanolysis, and the results showed that the highest ester conversion was 98% and obtained by using molar ratio of 1:6. However, ester conversion was decreased to 82% at molar ratio of 1:3.

Table 17.3 shows the chemical compounds of methyl ester obtained at oil to methyl acetate molar ratio of 1:6. Based on the GC-MS results' analysis in Table 17.3, it can be seen that with high amount of methyl ester on the product, triacetin had not been found on the product analysis. It shows that the optimization is necessary to obtain the best operating condition of the process for the future work.

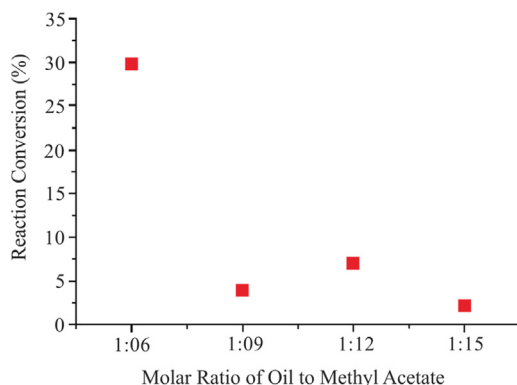


Figure 17.3 Effect of oil to methyl acetate molar ratio to the triglyceride conversion.

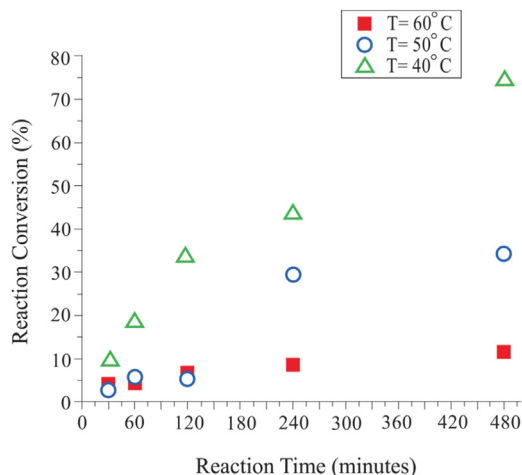
**Table 17.3** Chemical compounds of methyl ester at molar ratio of 1:6.

No.	Retention time, min	Area %	Chemical compound
1	39.239	0.60	Palmitic acid
2	42.257	6.90	Methyl ester
3	43.108	1.10	Methyl ester
4	43.784	0.09	Stearic acid
5	45.626	6.35	Palmitic acid
6	47.695	0.05	Palmitic acid
7	47.984	0.19	Mono-oleic acid
8	48.166	0.14	Methyl ester
9	49.607	0.20	Palmitic acid
10	49.736	7.73	Methyl ester
11	51.048	0.59	Oleic acid
12	51.225	0.16	Methyl ester
13	52.843	0.46	Methyl ester
14	53.012	0.93	Methyl ester
15	53.727	0.09	Stearic acid
16	54.033	0.34	Lauric acid

### 17.5.6 Effect of reaction time and temperature

In this case, the reaction temperatures were varied to 40°C, 50°C, and 60°C, while the interesterification process was carried out for 8 h and samples were taken at 0, 30, 60, 120, 240, and 480 min. The remaining parameters were constant, where the catalyst concentration was 0.5% w/w and oil to methyl acetate molar ratio was 1:6. This temperature range was chosen based on the catalyst activity, which is ranged between 20°C and 100°C (Mittlebach and Remschmidt, 2004). Freedman et al. (1984) also stated that transesterification process for peanut oil, cotton seeds oil, sunflower seeds oil, and soybean seeds oil should be carried out with oil to alcohol molar ratio of 1:6, catalyst concentration of 0.5%, and reaction temperature of 60°C. Fig. 17.4 shows the effect of reaction time and temperature to the triglyceride conversion.

Triglyceride conversion is decreasing with the increasing reaction temperature. Decreasing conversion from reaction temperature of 40°C–50°C was caused by the shifted reaction equilibrium to the reactant. Interesterification reaction is an exothermic reaction, which releases energy, furthermore increasing temperature will supply more heat. According to Le Chatelier's principle, the equilibrium will shifted to the reactant side (Kusumaningtyas et al., 2014). Rachimoellah et al. (2009) reported that since transesterification is an exotherm reaction, excess methyl acetate is needed to decrease the reaction temperature and shift the equilibrium reaction to the product side. Triglyceride conversion is also decreasing on the temperature increment from 50°C to 60°C, which was due to the reaction temperature used that was higher than the boiling point of methyl acetate, which is 56.1°C (Said et al., 2010). Hence,



**Figure 17.4** Effect of reaction time and temperature to the triglyceride conversion.

reaction between oil and methyl acetate at this reaction temperature is not effective and decreases the yield of methyl ester. However, longer reaction times give more chance for the oil to react with methyl acetate and resulted in more biodiesel product. In this case, the optimum operating condition was obtained at the reaction temperature and time of 40°C and 8 h, respectively, with triglyceride conversion of 73.96%.

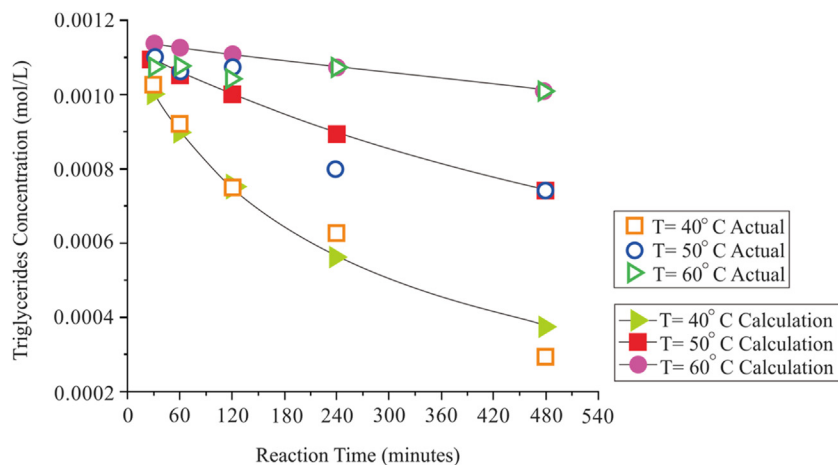
Chemical compounds of the product at the optimum condition are presented in Table 17.4. Based on Table 17.4, it was cleared that triacetin has not been found on the product analysis. It also can be concluded that the current operating condition was not the optimum condition for the interesterification reaction. However, glycerol was also found as the product. During the interesterification reaction between *Jatropha* oil and methyl acetate with KOH catalyst, the formation of triacetin di-(9-octadecenoyl)-glycerol inhibits the production of triacetin (Pristiyani, 2015). Brondani et al. (2020) suggested the higher reaction temperature and molar ratio of methyl acetate to oil in order to obtain higher yield of products.

### 17.5.7 Kinetic study

Fig. 17.5 shows the comparison between experimental data and the calculated triglyceride concentration as a function of reaction time and temperature. Based on the SSE between experimental data and the calculated triglyceride concentration, it can be concluded that the kinetic reaction of oil and methyl acetate interesterification process with the presence of NaOCH<sub>3</sub> catalyst can be approached by using second-order reversible kinetic model. Furthermore, based on the kinetic data for each temperature, kinetic factor ( $A$ ) and energy activation ( $E$ ) can be calculated by using Arrhenius equation. Table 17.5 shows the calculated kinetic rate of interesterification reaction as a function of reaction temperature.

**Table 17.4** Chemical compounds of methyl ester at reaction temperature of 40°C and reaction time of 8 h.

No.	Retention time, min	Area %	Chemical compound
1	45.050	0.20	Di-9-octadecenoyl glycerol
2	45.582	4.71	Palmitic acid
3	47.952	0.13	Mono-oleic acid
4	48.129	0.11	Oleic acid
5	49.692	5.31	Methyl ester
6	53.996	4.88	Lauric acid
7	55.365	4.04	Oleic acid
8	58.987	3.40	Lauric acid
9	59.984	0.42	Lauric acid


**Figure 17.5** Relation between  $C_{TG}$  experimental data and  $C_{TG}$  calculated as a function of reaction time and temperature.

**Table 17.5** Reaction rate constant.

Temperature (°C)	Reaction rate constant (L/mol.min)
40	1.5728
50	0.6753
60	0.2151

Regression analysis of reaction rate constant in Table 17.5 results in a preexponential factor ( $A$ ) of  $7.23 \times 10^{-15}$  L/mol.min and energy activation in terms of  $-E/R$  with 10,358 K/min. With a gas constant ( $R$ ) of 8.314 J/mol/K, the obtained energy



activation is 86,116.41 J/mol. Energy activation in this case was in line with the study reported by Casas et al. (2011), where the energy activation for conventional interesterification process was between 24,318 and 88,551 J/mol. The results are in accordance with Le Chatelier's principle, where reaction equilibrium will shift to the reactants for an exothermic reaction. As it can be seen in Table 17.5, the reaction rate is decreasing along with the increasing reaction temperature.

## 17.6 Conclusion

The data presented in this work demonstrate the feasibility of producing biodiesel fuels through interesterification reaction of Jatropha oil with methyl acetate in the presence of NaOCH<sub>3</sub> catalyst. Various parameters were studied, and it shows that the highest yield obtained in this study was 88.1% in oil to methyl acetate molar ratio of 1:6, reaction temperature of 50°C, and catalyst concentration of 1% w/w with 4 h of reaction time. Hence, highest catalyst concentration still can be used to achieve higher triglyceride conversion. Moreover, the resultant analysis of biodiesel product from various operating conditions shows the absence of triacetin. The kinetic model was fitted with the second-order reaction kinetic model. The energy activation was in line with the previous studies, which was 86,116.41 J/mol, while the preexponential factor (*A*) was  $7.23 \times 10^{-15}$  L/mol.min.

## Acknowledgment

The funding from the Ministry of Research, Technology, and Higher Education of Republic Indonesia, with contract number of 675/UN 37.3.1/LT/2016 is highly acknowledged.

## References

- AFDC, 2008. Biodiesel blends [WWW document]. U.S. Department of Energy, Energy Efficiency and Renewable Energy.
- Anwar, M., 2021. Biodiesel feedstocks selection strategies based on economic, technical, and sustainable aspects. *Fuel* 283, 119204.
- Asadikia, A., Rajabifard, A., Kalantari, M., 2021. Systematic prioritisation of SDGs: machine learning approach. *World Dev.* 140, 105269.
- Bertheau, P., 2020. Assessing the impact of renewable energy on local development and the Sustainable Development Goals: insights from a small Philippine island. *Technol. Forecast. Soc. Change* 153, 119919.
- Brondani, L.N., Ribeiro, J.S., Castilhos, F., 2020. A new kinetic model for simultaneous interesterification and esterification reactions from methyl acetate and highly acidic oil. *Renew. Energy* 156, 579–590.
- CAPP, 2020. World energy needs [WWW document]. Our energy needs world energy consumption demand. <https://www.capp.ca/energy/world-energy-needs/> (accessed 1.14.21).
- Casas, A., Ramos, M.J., Pérez, Á., 2011. Kinetics of chemical interesterification of sunflower oil with methyl acetate for biodiesel and triacetin production. *Chem. Eng. J.* 171, 1324–1332.

- Casas, A., Ramos, M.J., Pérez, Á., 2013. Production of Biodiesel through Interesterification of Triglycerides with Methyl Acetate. Nova Science Publishers, Inc., Hauppauge.
- Chen, R., Qin, Z., Han, J., Wang, M., Taheripour, F., Tyner, W., et al., 2018. Life cycle energy and greenhouse gas emission effects of biodiesel in the United States with induced land use change impacts. *Bioresour. Technol.* 251, 249–258.
- Dhawan, M.S., Barton, S.C., Yadav, G.D., 2020. Interesterification of triglycerides with methyl acetate for the co-production biodiesel and triacetin using hydrotalcite as a heterogenous base catalyst. *Catal. Today.* 375, 101–111.
- Dutta, A., 2019. Impact of carbon emission trading on the European Union biodiesel feedstock market. *Biomass Bioenergy* 128, 105328.
- EIA, 2020a. Global liquid fuels [WWW document]. Short-term energy outlook. [https://www.eia.gov/outlooks/steo/report/global\\_oil.php](https://www.eia.gov/outlooks/steo/report/global_oil.php) (accessed 2.2.21).
- EIA, 2020b. Biomass-based diesel and the environment [WWW document]. Biodiesel and the environment.
- Fangfang, F., Alagumalai, A., Mahian, O., 2021. Sustainable biodiesel production from waste cooking oil: ANN modeling and environmental factor assessment. *Sustain. Energy Technol. Assess.* 46, 101265.
- Ferrari, R.A., Pighinelli, A.L.M.T., Park, K.J., 2011. Biodiesel production and quality. In: Marco Aurelio Bernardes, D.S. (Ed.), *Biofuel's Engineering Process Technology*. InTech Europe, Croatia, pp. 221–240.
- Freedman, B., Pryde, E.H., Mounts, T.L., 1984. Variables affecting the yields of fatty esters from transesterified vegetable oils. *J. Am. Oil Chem. Soc.* 61, 1638–1643.
- Gadonneix, P., Sambo, A., Guobao, Z., Kim, Y.D., Teyssen, J., Lleras, J.A.V., et al., 2020. World Energy Issues Monitor 2020. World Energy Council, London.
- Gielen, D., Boshell, F., Saygin, D., Bazilian, M.D., Wagner, N., Gorini, R., 2019. The role of renewable energy in the global energy transformation. *Energy Strateg. Rev.* 24, 38–50.
- Hamzah, N.H.C., Khairuddin, N., Siddique, B.M., Hassan, M.A., 2020. Potential of *Jatropha curcas* L. as biodiesel feedstock in Malaysia: a concise review. *Processes* 8, 1–11.
- Huang, K.-H., Akoh, C.C., 1996. Enzymatic synthesis of structured lipids: transesterification of triolein and caprylic acid ethyl ester. *J. Am. Oil Chem. Soc.* 73, 245–250.
- IEA, 2020. Explore energy data by category, indicator, country or region [WWW document]. Data Stat. <https://www.iea.org/data-and-statistics?country=WORLD&fuel=EnergySupply&indicator=TPESbySource> (accessed 2.27.21).
- Kashyap, S.S., Gogate, P.R., Joshi, S.M., 2019. Ultrasound assisted intensified production of biodiesel from sustainable source as karanja oil using interesterification based on heterogeneous catalyst ( $\Gamma$ -alumina). *Chem. Eng. Process. Process Intensif.* 136, 11–16.
- Kato, E., Kurosawa, A., 2019. Evaluation of Japanese energy system toward 2050 with TIMES-Japan - deep decarbonization pathways. *Energy Procedia* 158, 4141–4146.
- Komintarachat, C., Sawangkeaw, R., Ngamprasertsith, S., 2015. Continuous production of palm biofuel under supercritical ethyl acetate. *Energy Convers. Manag.* 93, 332–338.
- Kusdiana, D., Saka, S., 2004. Two-step preparation for catalyst-free biodiesel fuel production: hydrolysis and methyl esterification. *Appl. Biochem. Biotechnol. A Enzym. Eng. Biotechnol.* 115, 781–791.
- Kusumaningtyas, R.D., Handayani, P.A., Rochmadi, R., Purwono, S., Budiman, A., 2014. Tin (II) chloride catalyzed esterification of high FFA jatropha oil: experimental and kinetics study. *Int. J. Renew. Energy Dev.* 3, 75–81.
- Kusumaningtyas, R.D., Pristiyani, R., Dewajani, H., 2016. A new route of biodiesel production through chemical interesterification of jatropha oil using ethyl acetate. *Int. J. ChemTech Res.* 9, 627–634.
- Lazdovica, K., Kampars, V., 2020. Influence of moisture and acids on the chemical interesterification of rapeseed oil and ability of the catalyst to promote the glycerol as an undesirable by-product. *J. Taiwan Inst. Chem. Eng.* 111, 110–118.
- Lopez, G., Aghahosseini, A., Bogdanov, D., Mensah, T.N.O., Ghorbani, N., Caldera, U., et al., 2021. Pathway to a fully sustainable energy system for Bolivia across power, heat, and transport sectors by 2050. *J. Clean. Prod.* 293, 126195.
- Ma, F., Hanna, M.A., 1999. Biodiesel production: a review. *Bioresour. Technol.* 70, 1–15.

- Ma, Q., Zhang, Q., Liang, J., Yang, C., 2021. The performance and emissions characteristics of diesel/biodiesel/alcohol blends in a diesel engine. *Energy Rep.* 7, 1016–1024.
- Maddikeri, G.L., Gogate, P.R., Pandit, A.B., 2014. Intensified synthesis of biodiesel using hydrodynamic cavitation reactors based on the interesterification of waste cooking oil. *Fuel* 137, 285–292.
- Maher, K.D., Bressler, D.C., 2007. Pyrolysis of triglyceride materials for the production of renewable fuels and chemicals. *Bioresour. Technol.* 98, 2351–2368.
- Masduki, M., Sutijan, S., Budiman, A., 2013. Kinetika Reaksi Esterifikasi Palm Fatty Acid Distilate (PFAD) menjadi Biodiesel dengan Katalis Zeolit-Zirconia Tersulfatasi. *J. Rekayasa Proses* 7, 59–64.
- Mittlebach, M., Remschmidt, C., 2004. *Biodiesel: The Comprehensive Handbook*, 1st Edition Boersdruck Ges.m.b.H., Vienna.
- Mufrodi, Z., Rochmadi, Sutijan, Budiman, A., 2014. Synthesis acetylation of glycerol using batch reactor and continuous reactive distillation column. *Eng. J.* 18, 29–39.
- Nguyen, T., Do, L., Sabatini, D.A., 2010. Biodiesel production via peanut oil extraction using diesel-based reverse-micellar microemulsions. *Fuel* 89, 2285–2291.
- Ogunkunle, O., Ahmed, N.A., 2019. A review of global current scenario of biodiesel adoption and combustion in vehicular diesel engines. *Energy Rep.* 5, 1560–1579.
- Pereira, T.C., Conceição, C.A.F., Khan, A., Fernandes, R.M.T., Ferreira, M.S., Marques, E.P., et al., 2016. Application of electrochemical impedance spectroscopy: a phase behavior study of babassu biodiesel-based microemulsions. *Spectrochim. Acta A Mol. Biomol. Spectrosc.* 168, 60–64.
- Pristiyani, R., 2015. Sintesis Biodiesel dan Fuel Bioadditive Triasetin secara Simultan dengan Metode Interesterifikasi Minyak Jarak (*Jatropha curcas*). Universitas Negeri Semarang.
- Rachimoellah, H.M., Resti, D.A., Zibbeni, A., Susila, I.W., 2009. Production of biodiesel through transesterification of avocado (*Persea gratissima*) seed oil using base catalyst. *J. Tek. Mesin* 11, 85–90.
- Rasyid, R., 2010. Pengaruh Suhu dan Konsentrasi Katalis pada Proses Esterifikasi Distilat Asam Lemak Minyak Sawit (DALMs) menjadi Biodiesel. *J. Kim. Val.* 1, 305–309.
- Said, M., Septiarty, W., Tutuwi, T., 2010. Studi Kinetika Reaksi pada Metanolisis Minyak Jarak Pagar. *J. Tek. Kim.* 17, 15–22.
- Santika, W.G., Urmee, T., Simsek, Y., Bahri, P.A., Anisuzzaman, M., 2020. An assessment of energy policy impacts on achieving Sustainable Development Goal 7 in Indonesia. *Energy Sustain. Dev.* 59, 33–48.
- Schuchardt, U., Sercheli, R., Matheus, R., 1998. Transesterification of vegetable oils: a review. *J. Braz. Chem. Soc.* 9, 199–210.
- Siregar, K., Tambunan, A.H., Irwanto, A.K., Wirawan, S.S., Araki, T., 2015. A comparison of life cycle assessment on oil palm (*Elaeis guineensis* Jacq.) and physic nut (*Jatropha curcas* Linn.) as feedstock for biodiesel production in Indonesia. *Energy Procedia* 65, 170–179.
- Sustere, Z., Kampars, V., 2015. Chemical interesterification of the rapeseed oil with methyl acetate in the presence of potassium tert-butoxide in tert-butanol. *Int. J. Eng. Tech. Res.* 3, 226–232.
- Teixeira, A.C.R., Sodr , J.R., Guarieiro, L.L.N., Vieira, E.D., De Medeiros, F.F., Alves, C.T., 2016. A review on second and third generation bioethanol production. In: *SAE Technical Papers*. SAE International.
- Traviss, N., Treadwell, M.D., 2018. Biodiesel vs diesel: a pilot study comparing exhaust exposures for employees at a rural municipal facility. *J. Air Waste Manag. Assoc.* 60, 1026–1033.
- Van Duren, I., Voinov, A., Arodudu, O., Firrisa, M.T., 2015. Where to produce rapeseed biodiesel and why? Mapping European rapeseed energy efficiency. *Renew. Energy* 74, 49–59.
- Widjanarko, D., Kusumaningtyas, R.D., Fathoni, A.A., 2020. Alteration of biodiesel properties and automotive diesel engine performance due to temperature variation of the transesterification process, *J. Rekayasa Kim. Lingkungan.*, 15. pp. 90–98.
- World Energy Council, 2020. *World energy trilemma index 2020*. London.
- Zulqarnain, Yusoff, M.H.M., Ayoub, M., Jusoh, N., Abdullh, A.Z., 2020. The challenges of a biodiesel implementation program in Malaysia. *Processes* 8, 1–18.