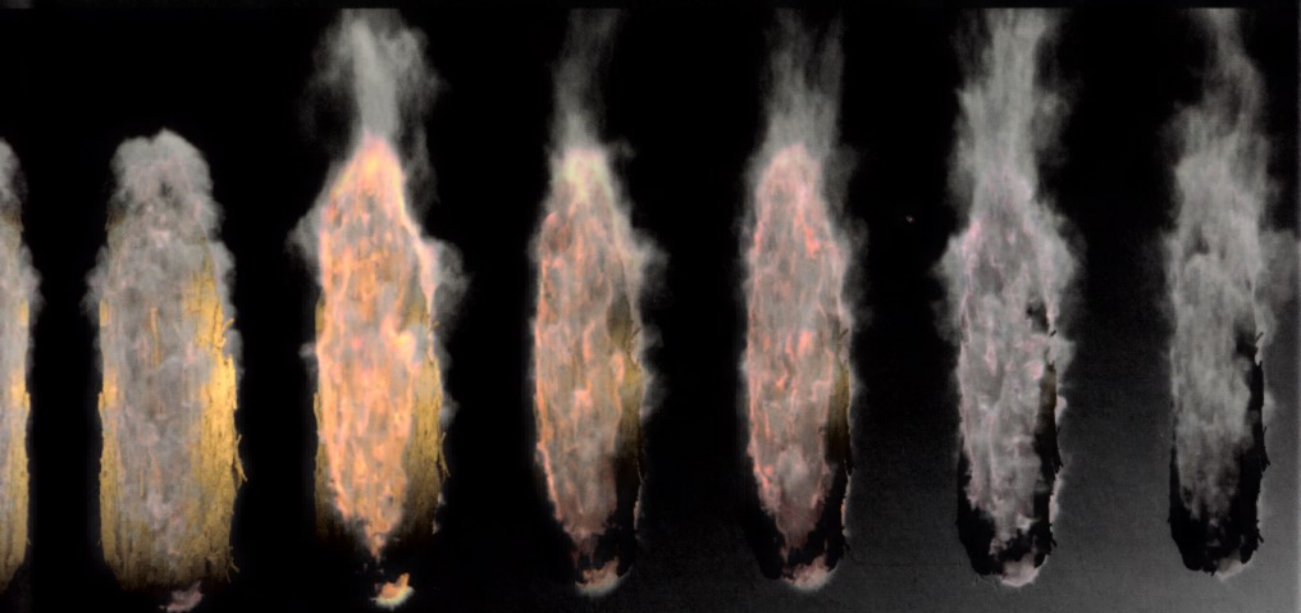


WILEY SERIES IN RENEWABLE RESOURCES

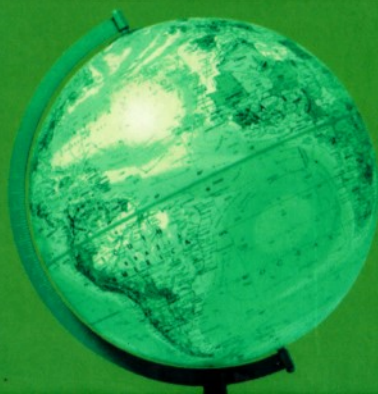
# Thermochemical Processing of Biomass

Conversion into Fuels, Chemicals and Power

Second Edition



Edited by Robert C. Brown



WILEY

# Contents

<b>List of Contributors</b>	<b>xv</b>
<b>Series Preface</b>	<b>xvii</b>
<b>Preface</b>	<b>xix</b>
<b>1 Introduction to Thermochemical Processing of Biomass into Fuels, Chemicals, and Power</b>	<b>1</b>
<i>Xiaolei Zhang and Robert C. Brown</i>	
1.1 Introduction	1
1.2 Thermochemical Conversion Technologies	5
1.2.1 Direct Combustion	5
1.2.2 Gasification	6
1.2.3 Pyrolysis	7
1.2.4 Solvent Liquefaction	8
1.3 Diversity of Products: Electric Power, Transportation Fuels, and Commodity Chemicals	8
1.3.1 Biopower	9
1.3.2 Biofuels	10
1.3.3 Bio-Based Chemicals	11
1.4 Economic Considerations	11
1.5 Environmental Considerations	12
1.6 Organization of This Book	13
References	14
<b>2 Condensed Phase Reactions During Thermal Deconstruction</b>	<b>17</b>
<i>Jake K. Lindstrom, Alexander Shaw, Xiaolei Zhang, and Robert C. Brown</i>	
2.1 Introduction to Condensed Phase Reactions During Thermal Deconstruction of Biomass	17
2.2 Thermochemical Processes	19
2.2.1 Processes Yielding Chiefly Solids	20
2.2.2 Processes Yielding Chiefly Liquids	22

2.2.3	Processes Yielding Chiefly Gases	24
2.3	Understanding Condensed Phase Reactions	28
2.3.1	Challenges in Investigating Condensed Phase Reactions	28
2.3.2	The Role of Cell Wall Structure in Thermal Deconstruction	30
2.3.3	Use of Computational Chemistry to Understand Thermal Deconstruction	34
2.4	Conclusions	41
	References	42
<b>3</b>	<b>Biomass Combustion</b>	<b>49</b>
	<i>Bryan M. Jenkins, Larry L. Baxter, and Jaap Koppejan</i>	
3.1	Introduction	50
3.2	Combustion Systems	51
3.2.1	Fuels	51
3.2.2	Types of Combustors	53
3.3	Fundamentals of Biomass Combustion	59
3.3.1	Combustion Properties of Biomass	59
3.3.2	Combustion Stoichiometry	65
3.3.3	Equilibrium	68
3.3.4	Rates of Reaction	68
3.4	Pollutant Emissions and Environmental Impacts	71
3.4.1	Oxides of Nitrogen and Sulfur	72
3.4.2	Products of Incomplete Combustion	74
3.4.3	Particulate Matter	74
3.4.4	Dioxin-Like Compounds	74
3.4.5	Heavy Metals	76
3.4.6	Radioactive Species	76
3.4.7	Greenhouse Gas Emissions	77
	References	77
<b>4</b>	<b>Gasification</b>	<b>85</b>
	<i>Karl M. Broer and Chad Peterson</i>	
4.1	Introduction	85
4.1.1	History of Gasification	85
4.1.2	Gasification Terminology	87
4.2	Fundamentals of Gasification	88
4.2.1	Heating and Drying	89
4.2.2	Pyrolysis	89
4.2.3	Gas–Solid Reactions	90
4.2.4	Gas-Phase Reactions	91
4.3	Feed Properties	91
4.4	Classifying Gasifiers According to Method of Heating	95
4.4.1	Air-Blown Gasifiers	95
4.4.2	Oxygen/Steam-Blown Gasifiers	96
4.4.3	Indirectly Heated Gasifiers	96
4.5	Classifying Gasifiers According to Transport Processes	98
4.5.1	Fixed Bed	99

4.5.2	Bubbling Fluidized Bed (BFB)	101
4.5.3	Circulating Fluidized Bed (CFB)	103
4.5.4	Entrained Flow	104
4.6	Pressurized Gasification	106
4.7	Products of Gasification	106
4.7.1	Gaseous Products	106
4.7.2	Char and Tar	109
4.8	System Applications	110
4.8.1	Process Heat	110
4.8.2	Combined Heat and Power (CHP)	117
4.8.3	Fuel and Chemical Synthesis	117
	Acknowledgement	118
	References	118
<b>5</b>	<b>Syngas Cleanup, Conditioning, and Utilization</b>	<b>125</b>
	<i>David C. Dayton, Brian Turk, and Raghubir Gupta</i>	
5.1	Introduction	125
5.2	Syngas Cleanup and Conditioning	126
5.2.1	Particulates	128
5.2.2	Sulfur	130
5.2.3	Ammonia Decomposition and HCN Removal	132
5.2.4	Alkalis and Heavy Metals	132
5.2.5	Chlorides	133
5.2.6	Tars and Soot	134
5.3	Syngas Utilization	137
5.3.1	Syngas to Gaseous Fuels	138
5.3.2	Syngas to Liquid Fuels	145
5.4	Summary and Conclusions	159
	References	164
<b>6</b>	<b>Fast Pyrolysis</b>	<b>175</b>
	<i>Robbie H. Venderbosch</i>	
6.1	Introduction	175
6.2	Fundamentals of Pyrolysis	175
6.2.1	Effects of the Chemical and Physical Structure of Biomass and Intermediate Products	176
6.2.2	Effects of Ash	179
6.3	Properties of Pyrolysis Liquids	184
6.4	Fast Pyrolysis Process Technologies	186
6.4.1	Ensyn (CFB)	186
6.4.2	Valmet/UPM (CFB)	188
6.4.3	BTG-BtL (Rotating-cone)	188
6.4.4	Dynamotive Technologies Corp	190
6.5	Applications of Pyrolysis Liquids	192
6.5.1	Combustion	192
6.5.2	Diesel Engines	193
6.5.3	Co-refining Options	194

6.5.4	Gasification	199
6.6	Chemicals	200
6.7	Catalytic Pyrolysis	202
6.8	Concluding Remarks	202
	Acknowledgement	203
	References	203
<b>7</b>	<b>Upgrading Fast Pyrolysis Liquids</b>	<b>207</b>
	<i>Karl O. Albrecht, Mariefel V. Olarte, and Huamin Wang</i>	
7.1	Introduction	207
7.2	Bio-oil Characteristics and Quality	208
7.2.1	Feedstock Factors Affecting Bio-oil Characteristics	209
7.2.2	Effect of Pyrolysis Operating Conditions on Bio-oil Composition	210
7.2.3	Need for Upgrading Bio-oil	211
7.3	Norms and Standards	212
7.4	Physical Pre-treatment of Bio-oil	213
7.4.1	Physical Filtration	213
7.4.2	Solvent Addition	213
7.4.3	Fractionation	214
7.5	Catalytic Hydrotreating	214
7.5.1	Stabilization Through Low Temperature Hydrotreating	214
7.5.2	Deep Hydrotreating	217
7.6	Vapor Phase Upgrading via Catalytic Fast Pyrolysis	218
7.6.1	CFP Chemistry	221
7.6.2	Key Factors Impacting Catalytic Fast Pyrolysis	221
7.6.3	Practical Catalytic Fast Pyrolysis of Lignocellulosic Biomass	223
7.7	Other Upgrading Strategies	223
7.7.1	Liquid Bio-oil Zeolite Upgrading and Co-processing in FCC	223
7.7.2	Reactions with Alcohols	227
7.8	Products	228
7.8.1	Liquid Transportation Fuel Properties	228
7.8.2	Chemicals	232
7.8.3	Hydrogen Production	235
7.9	Summary	235
	References	238
<b>8</b>	<b>Solvent Liquefaction</b>	<b>257</b>
	<i>Arpa Ghosh and Martin R. Haverly</i>	
8.1	Introduction	257
8.1.1	Definition of Solvent Liquefaction	257
8.1.2	History of Solvent Liquefaction	257
8.2	Feedstocks for Solvent Liquefaction	259
8.2.1	Feedstock Types	259
8.2.2	Benefits of Liquid Phase Processing	259
8.2.3	Reaction Types	261
8.2.4	Processing Conditions	262

8.3	Target Products	263
8.3.1	Bio-oil	263
8.3.2	Production of Fuels and Chemicals	264
8.3.3	Co-products	265
8.4	Processing Solvents	265
8.4.1	Inorganic Solvents	268
8.4.2	Polar Protic Solvents	271
8.4.3	Polar Aprotic Solvents	274
8.4.4	Ionic Liquids	276
8.4.5	Non-Polar Solvents	277
8.4.6	Influence of Process Conditions	278
8.5	Solvent Effects	283
8.5.1	Physical Effects	283
8.5.2	Solubility Effects	284
8.5.3	Structural Effects	287
8.5.4	Chemical Effects	287
8.6	Engineering Challenges	292
8.6.1	High Pressure Feed Systems	292
8.6.2	Separation of Solid Residue	293
8.6.3	Solvent Recovery and Recycle	293
8.7	Conclusions	294
	References	294
<b>9</b>	<b>Hybrid Processing</b>	<b>307</b>
	<i>Zhiyou Wen and Laura R. Jarboe</i>	
9.1	Introduction	307
9.2	Thermochemical Conversion of Lignocellulosic Biomass for Fermentative Substrates	308
9.2.1	Fast Pyrolysis for Production of Pyrolytic Substrates	308
9.2.2	Gasification of Biomass for Syngas Production	309
9.3	Biological Conversion of Fermentative Substrates into Fuels and Chemicals	310
9.3.1	Fermentation of Pyrolytic Substrates	310
9.3.2	Fermentation of Syngas	313
9.4	Challenges of Hybrid Processing and Mitigation Strategies	318
9.4.1	Pyrolysis–Fermentation Process	318
9.4.2	Gasification–Syngas Fermentation Process	320
9.5	Efforts in Commercialization of Hybrid Processing	322
9.6	Conclusion and Perspectives	323
	References	323
<b>10</b>	<b>Costs of Thermochemical Conversion of Biomass to Power and Liquid Fuels</b>	<b>337</b>
	<i>Mark M. Wright and Tristan Brown</i>	
10.1	Introduction	337
10.2	Electric Power Generation	338
10.2.1	Direct Combustion to Power	338

10.2.2	Gasification to Power	339
10.2.3	Fast Pyrolysis to Power	339
10.3	Liquid Fuels via Gasification	340
10.3.1	Gasification to Fischer-Tropsch Liquids	340
10.3.2	Gasification to Mixed Alcohols	341
10.3.3	Gasification to Gasoline	342
10.3.4	Gasification and Syngas Fermentation to Ethanol	343
10.3.5	Gasification and Syngas Fermentation to PHA and Co-product Hydrogen	343
10.4	Liquid Fuels via Fast Pyrolysis	344
10.4.1	Fast Pyrolysis and Hydroprocessing	344
10.4.2	Catalytic Fast Pyrolysis and Hydroprocessing	345
10.4.3	Fast Pyrolysis and Gasification to Fuels	346
10.4.4	Fast Pyrolysis and Bio-oil Fermentation to Ethanol	346
10.5	Liquid Fuels via Direct Liquefaction	348
10.6	Liquid Fuels via Esterification	349
10.7	Summary and Conclusions	349
	References	350
<b>11</b>	<b>Life Cycle Assessment of the Environmental Performance of Thermochemical Processing of Biomass</b>	<b>355</b>
	<i>Eskinder Demisse Gemechu, Adetoyese Olajire Oyedun, Edson Norgueira Jr, and Amit Kumar</i>	
11.1	Introduction	355
11.2	Life Cycle Assessment	356
11.2.1	Introduction to LCA and Life Cycle Thinking	356
11.2.2	Goal and Scope Definition	357
11.2.3	Life Cycle Inventory	357
11.2.4	Life Cycle Impact Assessment	358
11.2.5	Life Cycle Interpretation	359
11.2.6	Sensitivity and Uncertainty Analyses	359
11.3	LCA of Thermochemical Processing of Biomass	360
11.3.1	Overview of the Thermochemical Processing of Biomass	360
11.3.2	The Use of LCA to Promote Low Carbon Technologies	360
11.3.3	Review of LCA Studies on Thermochemical Processing of Biomass	360
11.4	Discussion on the Application of LCA for Thermochemical Processing of Biomass	369
11.4.1	Establishing Goal and Scope	369
11.4.2	Life Cycle Inventory Analysis	370
11.4.3	Life Cycle Impact Assessment	371
11.5	Conclusions	372
	Acknowledgements	373
	References	373
<b>Index</b>		<b>379</b>

# Thermochemical Processing of Biomass

Second Edition

Editor

**Robert C. Brown**, *Distinguished Professor of Engineering, Iowa State University, Ames, USA*

Series Editor

**Christian Stevens**, *Faculty of Bioscience Engineering, Ghent University, Belgium*

**A comprehensive examination of the large number of possible pathways for converting biomass into fuels and power through thermochemical processes**

Bringing together a widely scattered body of information into a single volume, this book provides complete coverage of the many ways that thermochemical processes are used to transform biomass into fuels, chemicals and power. Fully revised and updated, this new edition highlights the substantial progress and recent developments that have been made in this rapidly growing field since publication of the first edition and incorporates up-to-date information in each chapter.

*Thermochemical Processing of Biomass: Conversion into Fuels, Chemicals and Power, 2nd Edition* incorporates two new chapters covering condensed phased reactions of thermal deconstruction of biomass and life cycle analysis of thermochemical processing systems. It offers a new introductory chapter that provides a more comprehensive overview of thermochemical technologies. The book also features fresh perspectives from new authors covering such evolving areas as solvent liquefaction and hybrid processing.

Other chapters cover combustion, gasification, fast pyrolysis, upgrading of syngas and bio-oil to liquid transportation fuels, and the economics of thermochemically producing fuels and power, and more.

*Thermochemical Processing of Biomass: Conversion into Fuels, Chemicals and Power, 2nd Edition* will appeal to all academic researchers, process chemists, and engineers working in the field of biomass conversion to fuels and chemicals. It is also an excellent book for graduate and advanced undergraduate students studying biomass, biofuels, renewable resources, and energy and power generation.

For more information on the Wiley Series in Renewable Resources, visit [www.wiley.com/go/rrs](http://www.wiley.com/go/rrs)

- Features contributions by a distinguished group of European and American researchers offering a broad and unified description of thermochemical processing options for biomass
- Combines an overview of the current status of thermochemical biomass conversion as well as engineering aspects to appeal to the broadest audience
- Edited by one of Biofuels Digest's "Top 100 People" in bioenergy for six consecutive years

Cover Design: Wiley

Cover Images: Courtesy of Peter Ciesielski;

Education globe © Ingram Publishing/Alamy Stock Photo

[www.wiley.com](http://www.wiley.com)

**WILEY**



Also available  
as an e-book

ISBN 978-1-119-41757-6



9 781119 417576