Biotechnology in Agriculture and Forestry

Volume 66

Biotechnology in Agriculture and Forestry

Further volumes can be found at springer.com.

Volume 33: Medicinal and Aromatic Plants VIII (1995)
Volume 34: Plant Protoplasts and Genetic Engineering VI (1995)
Volume 35: Trees IV (1996)
Volume 36: Somaclonal Variation in Crop Improvement II (1996)
Volume 37: Medicinal and Aromatic Plants IX (1996)
Volume 38: Plant Protoplasts and Genetic Engineering VII (1996)
Volume 39: High-Tech and Microprogation V (1997)
Volume 40: High-Tech and Microprogation VI (1997)
Volume 41: Medicinal and Aromatic Plants X (1998)
Volume 42: Cotton (1998)
Volume 43: Medicinal and Aromatic Plants XI (1999)
Volume 44: Transgenic Trees (1999)
Volume 45: Transgenic Medicinal Plants (1999)
Volume 46: Transgenic Crops 1I (1999)
Volume 47: Transgenic Crops II (2001)
Volume 48: Transgenic Crops III (2001)
Volumes 1–48 were edited by Y.P.S. Bajaj†
Volume 49: Somatic Hybridization in Crop Improvement II (2001)
T. Nagata and Y.P.S. Bajaj (Eds.)
Volume 50: Cryopreservation of Plant Germplasm II (2002)
L.E. Towill and Y.P.S. Bajaj (Eds.)
Volume 51: Medicinal and Aromatic Plants XII (2002)
T. Nagata and Y. Ebizuka (Eds.)
Volume 52: Brassicas and Legumes: From Genome Structure to Breeding (2003)
T. Nagata and S. Tabata (Eds.)
Volume 53: Tobacco BY-2 Cells (2004)
T. Nagata, S. Hasezawa, and D. Inzé (Eds.)
Volume 54: Brassica (2004)
E.C. Pua and C.J. Douglas (Eds.)
Volume 55: Molecular Marker Systems in Plant Breeding and Crop Improvement (2005)
H. Lörz and G. Wenzel (Eds.)
Volume 56: Haploids in Crop Improvement II (2005)
C.E. Palmer, W.A. Keller, and K.J. Kasha (Eds.)
Volume 57: Plant Metabolomics (2006)
K. Saito, R.A. Dixon, and L. Willmitzer (Eds.)
Volume 58: Tobacco BY-2 Cells: From Cellular Dynamics to Omics (2006)
T. Nagata, K. Matsuoka, and D. Inzé (Eds.)
Volume 59: Transgenic Crops IV (2007)
E.C. Pua and M.R. Davey (Eds.)
Volume 60: Transgenic Crops V (2007)
E.C. Pua and M.R. Davey (Eds.)
Volume 61: Transgenic Crops VI (2007)
E.C. Pua and M.R. Davey (Eds.)
Volume 62: Rice Biology in the Genomics Era (2008)
H.-Y. Hirano, A. Hirai, Y. Sano and T. Sasaki (Eds.)
Volume 63: Molecular Genetic Approaches to Maize Improvement (2009)
A.L. Kriz and B.A. Larkins (Eds.)
Volume 64: Genetic Modification of Plants: Agriculture, Horticulture and Forestry (2010)
F. Kempken and C. Jung (Eds.)
Volume 65: Cotton: Biotechnological Advances (2010)
U.B. Zehr (Ed.)
Volume 66: Plant Biotechnology for Sustainable Production of Energy and Co-products (2010)
P.N. Mascia, J. Scheffran and J.M. Widholm (Eds.)

Peter N. Mascia • Jürgen Scheffran •
Jack M. Widholm
Editors

Plant Biotechnology for Sustainable Production of Energy and Co-products

Springer

Editors
Dr. Peter N. Mascia (deceased)
1535 Rancho
Conejo Blvd.
Thousand Oaks, CA 91320, USA

Prof. Dr. Jürgen Scheffran
Institute for Geography, Klima Campus
ZMAW, Hamburg University
Bundesstr. 53
20146 Hamburg, Germany
juergen.scheffran@zmaw.de

Prof. Dr. Jack M. Widholm
University of Illinois
Department of Crop Sciences
1201 W. Gregory, ERML
Urbana, Il 61801, USA
widholm@illinois.edu

ISSN 0934-943X
ISBN 978-3-642-13439-5 e-ISBN 978-3-642-13440-1
DOI 10.1007/978-3-642-13440-1
Springer Heidelberg Dordrecht London New York

Library of Congress Control Number: 2010935443

Cover design: WMXDesign GmbH, Heidelberg, Germany

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

This volume is dedicated to the late Peter Mascia, who had the foresight to see the future value of plant biomass and who was intimately involved in plant biotechnology and the commercial development of biomass crops. He is an editor of this volume since he helped plan a large part of it, but was unable to complete the work due to his untimely death on 6 May 2009.

Preface

This book is a collection of chapters concerning the use of biomass for the sustainable production of energy and chemicals–an important goal that will help decrease the production of greenhouse gases to help mitigate global warming, provide energy security in the face of dwindling petroleum reserves, improve balance of payment problems and spur local economic development.

Clearly there are ways to save energy that need to be encouraged more. These include more use of energy sources such as, among others, manure in anaerobic digesters, waste wood in forests as fuel or feedstock for cellulosic ethanol, and conservation reserve program (CRP) land crops that are presently unused in the US. The use of biofuels is not new; Rudolf Diesel used peanut oil as fuel in the first engines he developed (Chap. 8), and ethanol was used in the early 1900s in the US as automobile fuel [Songstad et al. (2009) Historical perspective of biofuels: learning from the past to rediscover the future. In Vitro Cell Dev Biol Plant 45:189–192). Brazil now produces enough sugar cane ethanol to make up about 50% of its transportation fuel needs (Chap. 4).

The next big thing will be cellulosic ethanol. At present, there is also the use of *Miscanthus x giganteous* as fuel for power plants in the UK (Chap. 2), bagasse (sugar cane waste) to power sugar cane mills (Chap. 4), and waste wood and sawdust to power sawmills (Chap. 7).

We have attempted to put together a distinguished group of authors to write chapters discussing many topics including the need for energy and the present problem of global warming that might be mitigated by using biomass instead of fossil fuels (Chap. 1). While ethanol is the most familiar fuel produced from biomass there are many other energy producing possibilities (Chap. 2). Of course, biomass can also be burned directly, and when mixed with coal helps decrease emissions of SO_2, NO_x, and non-renewable CO_2.

The overall general principals, possibilities and methods for designing plants for use as biomass feedstock are discussed in Chap. 3. Specific discussion of crops that produce sugar, starch or oil and trees and grasses can be found in Chaps. 4, 5, 6, 7 and 8. The general problems of invasiveness and gene dispersal and how to mitigate these problems are covered in Chaps. 9, 10 and 11. Chapter 12 describes models for integrated biorefineries that can produce many different products including industrial chemicals, and Chapter 13 describes models for the use of maize stover to supply heat and power for ethanol plants.

Other topics covered include new agricultural systems for biomass production for biofuels (Chap. 14), the life cycle analysis of biofuels (Chap. 15) and overall discussions of the many uses of biomass and possible cautions and criteria for standards for biomass sustainability and certification (Chap. 16).

Clearly, much development is still needed to fulfill the dream of the widespread use of biomass for energy and co-products. One of the biggest key questions is when will the production of cellulosic ethanol or other fuels become economically competitive with other liquid fuels. The infrastructure is in place to utilize ethanol if costs become competitive. We feel confident that progress will be made in cellulosic processing and fermentation due to the large amount of current interest and research and development funding so that this goal should be realized. Clearly, in the end, economics will decide the winners among the many crops and processes. The next decade should be exciting to see the winners and losers in the race to produce biomass for energy and co-products and to see how effective this is for the good of the world.

We have attempted to clarify the units used in the actual chapters, but the following list may be useful for comparative purposes.

Energy value of ethanol = 67% that of gasoline
1 kilogram (kg) = 2.205 pounds
1 metric ton = 1,000 kg = 1 mega gram (Mg) = 1 million g = 2,205 pounds
1 giga ton (Gt) = 1 billion metric tons
1 short ton = 2,000 pounds = 0.907 metric ton
1 hectare (ha) = 2.47 acres
1 liter (l) = 0.265 gallons
1 barrel (bbl) = 42 gallons = 158.8 l
1 meter (m) = 1.094 yard = 3.28 ft
MJ (megajoule) = million joules
BTU (British thermal unit) = 1,054.5 joules or 252 calories
KW (kilowatt) = 1,000 joules
KWH (kilowatt hour) = 3.6 MJ
TW (terawatt) = 1 million MW (megawatts)
MW (megawatt) = 1 million watts

June 2010 Jack M. Widholm

Contents

Part A Introduction to Biofuels

1 Introduction Overview: World Energy Resources and the Need for Biomass for Energy and Lower Fossil Carbon Dioxide Emissions 3
Charles E. Wyman
1.1 Introduction 3
1.2 World Dependence on Petroleum 4
1.3 Oil and Global Climate Change 7
1.4 What are our Options to Reduce Petroleum Use? 7
1.5 Why Biomass for Transportation? 8
1.6 Overview of Conversion Approaches 10
1.6.1 Biomass Composition 10
1.6.2 Higher Temperature Processes 11
1.6.3 Lower Temperature Processes 13
1.6.4 Comparison of Conversion Options 15
1.7 What is the Goal and How Much Biomass will be Needed? 16
1.8 Challenges to Commercial Applications 18
1.9 Closing Thoughts 19
References 21

2 Designing Biomass Crops with Improved Calorific Content and Attributes for Burning: a UK Perspective 25
Gordon G. Allison, Mark P. Robbins, José Carli, John C. Clifton-Brown, and Iain S. Donnison
2.1 The Need for Non-Food Energy Crops 25
2.2 Biomass Combustion Technologies 26
2.2.1 The Combustion Process 26
2.2.2 Biomass as a Feedstock for Combustion 27

2.3 Lignocellulose 28
2.3.1 Structure and Composition of the Plant Cell Wall 28
2.3.2 Plant Cell Wall Architecture 29
2.4 The Effect of Chemical Composition on Feedstock Properties 30
2.5 Energy Crops for Combustion Processes in the European Union 31
2.5.1 Miscanthus Species 33
2.5.2 Switchgrass 35
2.5.3 Willow and Poplar 36
2.5.4 Reed Canary Grass 38
2.6 Technologies for Crop Design 38
2.6.1 Modification of Hemicellulose and Cellulose 38
2.6.2 Modification of Lignin 39
2.6.3 Breeding Strategies 42
2.6.4 Chemical Phenotyping and High-Throughput Screening 42
2.6.5 Case Study: Variation in Cell Wall Composition Between 249 *Miscanthus* Genotypes 44
2.7 Conclusions and Future Perspectives 46
References 47

3 Designing Plants To Meet Feedstock Needs 57
Peter N. Mascia, Michael Portereiko, Mark Sorrells, and Richard B. Flavell
3.1 Introduction 57
3.2 Feedstock Crops 58
3.3 Trait Improvement 61
3.4 Molecular Markers for Breeding and Genetic Mapping 64
3.5 Comparative Genomics 66
3.6 Heterosis 67
3.7 Improving Traits by Molecular Plant Breeding 68
3.8 Transgenic Traits 72
3.8.1 First Generation Transgenic Traits 72
3.8.2 Transgenic Output Traits 73
3.8.3 Co-products 76
3.8.4 Genetic Confinement and Prevention of Seed Formation 77
3.9 Concluding Remarks 79
References 80

Part B Specific Biofuel Feedstocks

4 Engineering Advantages, Challenges and Status of Sugarcane and other Sugar-Based Biomass Resources 87
Ricardo A. Dante, Plinio T. Cristofoletti, and Isabel R. Gerhardt
4.1 Introduction 87
4.1.1 Sugar-Based Industry and Ethanol Uses 87
4.1.2 Sugarcane Production System 90

4.2 Biotechnology and Breeding Strategies for Increasing Sugarcane Sucrose Yields 91
4.2.1 Photosynthetic Capacity of Sugarcane and the Sink–Source Relationship: What Determines Sucrose Accumulation? 91
4.2.2 Sugarcane Biotechnology 94
4.2.3 Molecular Markers in Sugarcane Breeding 98
4.3 Other Sugar Crops Suitable for Ethanol Production 99
4.4 Perspectives 101
References 102

5 High Fermentable Corn Hybrids for the Dry-Grind Corn Ethanol Industry 111
Joel E. Ream, Ping Feng, Inigo Ibarra, Susan A. MacIsaac, Beena A. Neelam, and Erik D. Sall
5.1 Introduction 111
5.2 Value of High Fermentable Corn Hybrids 112
5.3 Factors Influencing the Fermentability of Corn Grain 114
5.4 Measuring Corn Grain Fermentability 116
5.4.1 NIT Calibration 116
5.4.2 Reference Chemistry 117
5.4.3 NIT Calibration 118
5.4.4 Commercial Validation of NIT Calibration 119
5.5 Designation of High Fermentable Corn Hybrids 121
5.6 Opportunities to Increase Corn Grain Fermentability 122
5.7 Summary 123
References 123

6 Engineering Advantages, Challenges and Status of Grass Energy Crops 125
David I. Bransby, Damian J. Allen, Neal Gutterson, Gregory Ikonen, Edward Richard Jr, William Rooney, and Edzard van Santen
6.1 Introduction 125
6.2 Miscanthus 126
6.2.1 *Miscanthus* Phylogeny and Growth 127
6.2.2 Genetic Improvement of *Miscanthus* 127
6.2.3 Conventional Breeding Challenges 128
6.3 Switchgrass 131
6.3.1 Switchgrass Phylogeny and Growth 132
6.3.2 Genetic Improvement of Switchgrass 133
6.3.3 Conventional Breeding Challenges 134
6.4 Sugarcane 136
6.4.1 Sugarcane Phylogeny and Growth 136
6.4.2 Genetic Improvement Needs 139
6.4.3 Genetic Improvement Strategies 141

6.5 Sorghum 142
6.5.1 Sorghum Phylogeny and Growth 142
6.5.2 Genetic Improvement 144
6.6 Integration of Grasses into Cellulosic Biomass Supply Systems .. 146
6.7 Conclusions 147
References 147

7 Woody Biomass and Purpose-Grown Trees as Feedstocks for Renewable Energy 155
Maud A.W. Hinchee, Lauren N. Mullinax, and William H. Rottmann
7.1 The Forest Industry and Renewable Energy 155
7.2 Biopower 158
7.2.1 Processes for Energy Production from Woody Biomass 159
7.2.2 Characteristics of Wood Feedstock that Impact Bioenergy Production 164
7.2.3 Tree Species for Biopower 167
7.2.4 Softwood Species for Bioenergy 172
7.3 Liquid Biofuels 173
7.3.1 Cellulosic Ethanol 173
7.3.2 Conversion Processes 175
7.3.3 Other Cellulosic Liquid Fuels 179
7.3.4 Feedstock Characteristics Affecting Biofuel Production 180
7.4 Purpose-Grown Trees for Renewable Energy 181
7.4.1 Genetic Improvement for Productivity 184
7.4.2 Genetic Improvement for Wood Properties 191
7.5 Sustainable Production of Purpose-Grown Trees 193
7.6 Conclusion 197
References 198

8 Engineering Status, Challenges and Advantages of Oil Crops 209
Richard F. Wilson and David F. Hildebrand
8.1 Global Trends in Supply and Demand for Edible Oils 209
8.1.1 Constraints on the Use of Edible Crop Products for Biofuel 209
8.1.2 Availability and Cost of Biodiesel Feedstocks 212
8.1.3 Sustainability 216
8.2 Technology Trends to Further Enhance the Sustainability of Edible Oils for Biofuel 218
8.2.1 Physical Properties of Edible Oils 218
8.2.2 Genetic Modification of the Physical Properties of Edible Oils 221
8.2.3 Development of Markets for Edible Oils with Modified Traits 222

8.3 Advances in Genetically Modified Oil Trait Technology in Major Oilseed Crops 223
8.3.1 Biological Basis for Trait Modified Oils 223
8.3.2 Modified Oil Traits in the Commercial Pipeline 226
8.4 Advances in Genetically Modified Oil Trait Technology in New or Underdeveloped Oilseed Crops 229
8.4.1 New Crop Oils for Industrial Chemicals 229
8.4.2 Biological Basis for Industrial Oil Traits 241
8.5 Conclusions 247
References 248

Part C Mitigating Invasiveness

9 Invasive Species Biology, Ecology, Management and Risk Assessment: Evaluating and Mitigating the Invasion Risk of Biofuel Crops 263
Jacob N. Barney, Joseph M. DiTomaso
9.1 Biofuel Crops and Invasive Species 263
9.2 Invasive Species Biology and Ecology 265
9.3 Assessing the Invasive Risk of Biofuel Crops 267
9.3.1 Risk Assessment 268
9.3.2 Species biology 269
9.3.3 Niche Modeling 271
9.3.4 Propagule Biology 272
9.3.5 Habitat Susceptibility 273
9.3.6 Hybridization Potential 274
9.3.7 Competitive Interactions 274
9.4 Mitigating the Invasion Risk Along the Biofuel Chain 275
9.4.1 Crop Development 276
9.4.2 Crop Importation and Dissemination 277
9.4.3 Crop Production 277
9.4.4 Feedstock Harvesting, Processing, Transport, and Storage .. 278
9.4.5 Feedstock Conversion 279
9.5 Response to Biofuel Crop Escapes 279
9.5.1 Eradication Techniques 279
9.6 Conclusions 280
References 281

10 Gene Flow in Genetically Engineered Perennial Grasses: Lessons for Modification of Dedicated Bioenergy Crops 285
Albert P. Kausch, Joel Hague, Melvin Oliver, Lidia S. Watrud, Carol Mallory-Smith, Virgil Meier, and C. Neal Stewart
10.1 Introduction 285
10.2 Gene Flow in Glufosinate-Resistant Grasses 287

10.3 Gene Flow in Glyphosate-Resistant Creeping Bentgrass 289
10.3.1 Gene Flow via Pollen in Glyphosate-Resistant Bentgrass 290
10.4 Gene Flow via Seed Scatter 292
10.4.1 Gene Flow via Seed Escape in Glyphosate-Resistant Bentgrass 293
10.5 Future Impacts of Gene Flow from Glyphosate-Resistant Creeping Bentgrass 294
10.6 Conclusions 294
References 296

11 Genetic Modification in Dedicated Bioenergy Crops and Strategies for Gene Confinement 299
Albert P. Kausch, Joel Hague, Melvin Oliver, Yi Li, Henry Daniell, Peter Mascia, and C. Neal Stewart Jr
11.1 Introduction 299
11.2 Methods for Gene Confinement in Genetically Engineered Plants . 300
11.2.1 Physical, Spatial, Mechanical and Temporal Control 300
11.2.2 Pollen Sterility 301
11.2.3 Cytoplasmic Male Sterility, Chloroplast Transformation and Maternal Inheritance 302
11.2.4 Seed-Based Gene Confinement 304
11.2.5 Perceived Risks Associated with GURTs 304
11.2.6 Gene Deletor System 309
11.2.7 Total Sterility 309
11.2.8 Total Sterility and Confinement Expression Systems 310
11.3 Regulatory Issues for Perennial Bioenergy-Dedicated Crops 311
11.4 Conclusions 311
References 313

Part D Models for Uses of Biomass Feedstocks

12 Integrated Biorefineries–A Bottom-Up Approach to Biomass Fractionation 319
Birgit Kamm
12.1 Introduction 319
12.2 Biorefinery Technologies and Biorefinery Systems 321
12.2.1 Background 321
12.2.2 Lignocellulosic Feedstock Biorefinery 322
12.2.3 Whole Crop Biorefinery 324
12.2.4 Green Biorefinery 327
12.2.5 The Two Platforms Biorefinery Concept 329
12.3 Platform Chemicals 330
12.3.1 Background 330

12.3.2 The Role of Biotechnology in Production of Platform Chemicals 332
12.3.3 Green Biomass Fractionation and Energy Aspects 334
12.3.4 Mass and Energy Flows for Green Biorefining 334
12.3.5 Assessment of Green Crop Fractionation Processes 337
12.4 Green Biorefinery: Economic and Ecologic Aspects 338
References 339

13 Heat and Power Production from Stover for Corn Ethanol Plants .. 345
Shahab Sokhansanj, Sudhagar Mani, Cannayen Igathinathane, and Sam Tagore
13.1 Introduction 345
13.2 Economics of Stover Supply to the Ethanol Plant 347
13.2.1 Stover Collection 348
13.2.2 Preprocessing 349
13.2.3 Stover Transport 349
13.2.4 On-Site Storage and Fuel Preparation 350
13.3 Costs 350
13.3.1 Cost of Biomass Collection 350
13.3.2 Preprocessing Costs 351
13.3.3 Transport Costs 352
13.3.4 On-Site Fuel Storage and Preparation 353
13.3.5 Total Cost of Biomass Fuel Delivered to the Burner 353
13.4 Heat and Power Production 353
13.4.1 Process Heat Generation 355
13.4.2 Combined Heat and Power Generation 357
13.5 Concluding Remarks 360
References 361

Part E Agricultural Fit of Biomass Crops and Lifecycle Analysis and Criteria

14 The Problem is the Solution: the Role of Biofuels in the Transition to a Regenerative Agriculture 365
Daniel G. De La Torre Ugarte and Chad C. Hellwinckel
14.1 Introduction 365
14.1.1 The Recent Price Bubble 366
14.1.2 Long-Term Factors 368
14.2 The Socio-Economic Impacts of Industrial Agriculture 370
14.3 The Environmental Footprint of Industrial Agriculture 371
14.3.1 Soil Loss 371
14.3.2 Fossil Energy Dependence 372
14.3.3 Greenhouse Gas Emissions 373

14.4 Future Agricultural Policy: What is Needed? 374
14.4.1 How do Agricultural Prices Impact Food Security, and Environmental Performance? 374
14.4.2 The Role of Biofuels 377
14.4.3 Transformative Investments in a New Agriculture 378
14.4.4 Structural Shift 381
14.5 Final Remarks 383
References 383

15 Life-Cycle Analysis of Biofuels 385
Michael Wang
15.1 Introduction 385
15.2 Potential Biofuel Production Pathways 386
15.3 Biofuel Life Cycle Analysis Boundary 387
15.4 Life-Cycle Analysis Models for Biofuels 389
15.4.1 The GREET Model at Argonne National Laboratory 389
15.4.2 The Lifecycle Emissions Model at the University of California at Davis 390
15.4.3 The GHGenius Model in Canada 391
15.4.4 The E3 Database from Ludwig-Bölkow-Systemtechnik 391
15.5 Life-Cycle Energy and Greenhouse Gas Emission Results of Key Biofuel Pathways with GREET Simulations 392
15.5.1 Corn and Cellulosic Ethanol 392
15.5.2 Sugarcane Ethanol 395
15.5.3 Biodiesel and Renewable Diesel from Soybeans 396
15.5.4 Corn Butanol 400
15.6 Key Life-Cycle Analysis Issues and Uncertainties 402
15.6.1 Direct and Indirect Land Use Changes 402
15.6.2 Co-Product Issues for Biofuel Life-Cycle Analyses 403
15.6.3 Other Environmental Sustainability Issues 405
15.7 Conclusions 406
References 407

16 Criteria for a Sustainable Bioenergy Infrastructure and Lifecycle 409
Jürgen Scheffran
16.1 Introduction 409
16.2 Optimizing Bioenergy Lifecycle and Infrastructure 411
16.2.1 Bioenergy Supply Chain and Lifecycle 411
16.2.2 The Integrated Biorefinery—From Feedstocks to Bioproducts 412
16.2.3 Biomass Transportation Infrastructure 414
16.3 Biogenic Wastes and Residues 416
16.4 Energy Balance and Efficiency 419

16.5 Carbon Intensity and Conservation of Carbon Stocks 420
16.6 Soil Protection, Land Use and Food Security 423
16.7 Water Needs and Water Crisis 427
16.8 Wildlife, Biodiversity and Environmental Impact 430
16.9 Health, Safety and Social Criteria 432
16.9.1 Health and Safety 432
16.9.2 Decent Working Conditions 433
16.9.3 Fair Feedstock Production and Land Rights 433
16.10 Sustainability Standards and Certification Schemes for Bioenergy ... 433
16.11 Conclusion 443
References 443

Index 449