Yogendra Shastri · Alan Hansen
Luis Rodríguez · K.C. Ting *Editors*

Engineering and Science of Biomass Feedstock Production and Provision

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Preface

The focus on lignocellulosic biomass-based fuels, also known as second-generation biofuels, has been increasing substantially in recent years. This is evident from the number of journals dedicated to this topic, the number of research papers published, and the number of conferences organized globally. The criticality of efficient and reliable biomass feedstock production and provision (BFPP) for sustainable lignocellulosic biofuel production is also now well acknowledged. It has further been realized that a significant shift from conventional agricultural practices may be needed to achieve the proposed biomass production targets, such as the well-known billion ton target for the United States.

Our own research on this topic started in 2008 as part of a research program funded through the Energy Biosciences Institute co-located at the University of Illinois at Urbana-Champaign and the University of California, Berkeley. The field was nascent at that stage, and the fundamental understanding of various aspects of BFPP was developing through many concurrent research initiatives. Most of the relevant information pertained to agricultural residue such as corn stover. Information specific to dedicated energy crops such as perennial grasses was sporadic in the literature. Subsequently, we have seen an explosion of research output in the last few years in the form of journal papers, conference presentations, technical reports, feasibility studies, and white papers. New knowledge was being generated and novel challenges were being identified. However, the consolidation of this new knowledge in the form of a comprehensive book is still lacking. We have interacted frequently with researchers working in this and related fields as well as with students initiating research on this topic. These interactions have emphasized the need for a comprehensive book on this topic that covers all the aspects of BFPP. Moreover, the topic of bioenergy, and consequently BFPP, has been the basis of many new interdisciplinary educational degree/certificate programs. We realize that a book on the topic of BFPP will be of significant value to the students and instructors participating in these programs.

Therefore, when Springer Science approached us in January 2012 to write a book in the area of bioenergy, we were very excited to suggest biomass feedstock production and provision as a potential topic of the book. The field had matured enough to justify the publication of a compendium of recent progress and future challenges. We are very glad that Springer Science wholeheartedly supported the idea and recognized the value of a book in this field.

Finalizing the scope of the book was an important step. The topic of BFPP comprises basic sciences, engineering, economics, policy and regulation, and social sciences. Engineering plays a key role in translating the scientific understanding into practical solutions. Given the importance of engineering and our strong background in this area, we decided to focus the book primarily on the engineering aspects of BFPP. As part of our own research, we have identified various subsystems or tasks of BFPP, namely, preharvest crop monitoring, harvesting, storage, and transportation. Our research also integrates these tasks in a holistic manner through a systems informatics and analysis task. The book follows a similar philosophy and reviews the recent developments on each of these topics. Engineering properties of biomass play an important role in all tasks described above. We, therefore, included a chapter on describing these properties and their measurement methods. We further realized that the BFPP system is impacted by aspects of agronomy, including crop establishment and management, and have included a chapter that focuses on this topic. We also recognized that the topic of BFPP would be of relevance not only to engineers but also to other stakeholders, such as farmers, plant managers, investors, policy makers, and businesses. Decisions for these stakeholders must account for the long-term sustainability viewed through the policy framework. We, therefore, have included a chapter elaborating on these issues, which makes this book really unique. There was a thought of including a chapter on processing of biomass into fuels and other products. However, we believe that there are many excellent books already published on this topic to which interested readers can refer.

Individual chapters provide an overview of the challenges, review current status, identify knowledge gaps, and provide future research directions. The chapters primarily discuss the production and provision of dedicated energy crops such as switchgrass and Miscanthus. However, literature on agricultural residue, green energy crops, and short rotation woody biomass is also discussed wherever appropriate. The target audience for the book includes engineers (agricultural, chemical, mechanical, civil), agronomists, researchers, undergraduate and graduate students, policy makers, bioenergy industries/businesses, farmers, and farm consultants. We also hope that the book will be used as learning material for classroom or laboratory instructions on this topic. A few pilot-scale biomass processing facilities have recently been set up, and focus will soon shift on setting up commercial scale facilities. The material presented in this book will provide valuable guidelines for setting up such facilities. We believe that the book will serve as an authoritative treatise on BFPP with particular emphasis on the engineering aspects. While we assume that the readers will have a preliminary understanding of the bioenergy systems and agricultural operations, all the chapters would be easy to comprehend for most readers. The readers can jump to a specific chapter of interest without going through the preceding chapters.

There are several people to acknowledge for the successful completion of the book. First and foremost, we would like to thank all the authors for their contributions. They readily accepted our request for contribution and have been very cooperative during the submission, review, and revision stages. The number of researchers working in this area is small, albeit increasing, and all the authors contributing to this book are leading researchers in their respective fields. We are, therefore, really glad that we have been able to bring them together for the purpose of this book.

We would also like to thank Springer Science for their interest in publishing in this area. The publishing house and its staff have provided us with excellent support throughout the preparation of the book. Ms. Hannah Smith, Associate Editor, Plant Sciences, helped us during the initial stages of conceptualizing the book, providing feedback on the scope, and finalizing the contributors. We thank the reviewers for providing us with valuable inputs and suggestions. Ms. Diane Lamsback, Developmental Editor, has subsequently provided very good support during the preparation and editing of the individual chapters and the compilation of the book. Needless to say, the book would not have come out without their support.

Finally, we would like to acknowledge the Energy Biosciences Institute for providing the unique opportunity to many contributing authors to work together on this important topic.

Mumbai, India
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Chapter 1
Biomass Feedstock Production and Provision: Overview, Current Status, and Challenges

Yogendra Shastri and K.C. Ting

Abstract Biomass-based renewable energy will play a critical role in meeting the future global energy demands. Lignocellulosic biomass, such as agricultural residue, perennial grasses, and woody biomass, will constitute a major portion of the feedstock for these biomass-based energy systems. However, successful transition to this second-generation bioenergy system will require cost-efficient, reliable, and sustainable biomass feedstock production and provision (BFPP). The BFPP system includes the operations of agronomic production of energy crops and physical processing and handling/delivery of biomass, as well as other enabling logistics. On the technical side, biological, physical, and chemical sciences need to be integrated with engineering and technology to ensure effective and efficient production of biomass feedstock. However, low energy and bulk densities, seasonal availability, and distributed supply create unique challenges for BFPP. Lack of experience and established standards provide additional challenges for large-scale production and provision of energy crops. The aim of this book is to summarize the current state of knowledge, identify research gaps, and provide future research directions on the topic of BFPP. Towards that end, the goal of this chapter is to set the foundation for the subsequent chapters that focus on specific components within this system. This BFPP system and its components are briefly described, current status and challenges are identified, and the research needs are highlighted. A typical production system based on current understanding and technological availability is also described. The chapter, therefore, provides an introduction to the advanced chapters that appear subsequently in the book.

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1.1 Introduction

Availability of energy is very critical to the survival, well-being, and development of the society. The industrial revolution spurred tremendous development during the past century and has led to unprecedented energy demands throughout the globe. The rising global population has further intensified the energy-consumption patterns. The majority of the world's energy demand is presently being met by nonrenewable fossil fuels, mainly coal, petroleum, and natural gas [1]. However, these fuel reserves are rapidly depleting [2]. Moreover, emissions resulting from fossil fuel consumption, such as CO_2, CH_4, and N_2O, are believed to be driving the global warming trends [3], as well as being the cause of acid rain and various health problems for humans and animals. There are also implications for the national economy and security of various countries. The long-term sustainability of the prevailing energy-consumption practices, therefore, is being questioned.

These concerns have been instrumental in the drive towards alternate, renewable, regional, and "clean" sources of energy, such as biomass, solar, wind, and hydro. Although the overall contribution of renewable energy is presently not significant, it is expected that with the development of more efficient technologies, these energy sources will become cost-competitive with the conventional nonrenewable sources. Among these renewable sources, biomass holds a distinct advantage for primarily two reasons. First, the biomass-based resources can be converted to liquid fuels such as ethanol and butanol, which can readily fit into the existing transportation infrastructure, thereby requiring minimal modifications. Since the transportation sector is a major consumer of fossil fuels, biomass-based fuels can make a significant impact. Second, the availability of biomass-based resources is relatively stable and predictable as compared to wind and solar [4, 5]. Biomass can also be stored for later use. In addition to this, biomass can also be converted to heat by direct combustion, power by direct combustion or co-firing with coal, and other value-added products and chemicals, such as glycerol and lactic acid [6].

There are primarily two sources of biomass: forestry and agriculture. For each of these sources, the available resources can be classified as primary, secondary, and tertiary [4]. Currently, the production of biofuels and bioproducts is being achieved mainly from the conventional agricultural food crops such as sugarcane in Brazil, corn and soybean in the United States, as well as Europe, and palm oil in Asia. The agricultural practices to produce these crops have improved substantially over centuries, and the processes to convert these sources into fuel and products are also well understood. These systems, therefore, are economically viable. However, the use of these food crops for fuel production has spurred the "food vs. fuel" debate in recent years [7]. It has been argued that use of these crops for fuel production is increasing food prices and impacting the availability of food resources. Moreover, cascading effects of increased fuel production are leading to indirect land use change in different parts of the world, thereby also mitigating the environmental and social benefits of biofuels [8]. Therefore, lignocellulosic biomass, such as dedicated perennial grasses, agricultural crop residue, forestry residue, and short rotation woody biomass, have emerged as the more sustainable biomass resources [4, 9].

The processing of lignocellulosic biomass to fuel is more challenging compared to that of carbohydrates (starch and sugars) due to biomass recalcitrance [10]. Lignocellulosic biomass can be converted to fuels and value-added products using two different routes: biochemical and thermochemical [11]. The biochemical route involves pretreatment, hydrolysis, and fermentation as the major processing steps and is mainly used to produce ethanol [12]. The thermochemical route involves gasification to produce syngas, which can then be converted to a variety of products and chemical building blocks using Fischer-Tropsch synthesis and water-gas shift reaction [13]. The thermochemical route also includes pyrolysis to produce bio-oil, which can be refined into separate fractions [13]. There have been significant research efforts to make these conversion processes more efficient and cost-competitive through development in science and technology. It has been argued that these possibilities can be used to develop a sustainable bio-based economy driven by biomass resources [14]. Such a bio-based economy can achieve its sustainability mission by reducing environmental emissions, achieving energy security, and stimulating rural economy and social well-being.

An important precursor for the success of the proposed bio-based economy is a continuous, reliable, and cost-effective supply of biomass from sources such as farms and forests to the biorefinery that is able to satisfy the expected high demand rates while maintaining the quality. This constitutes the biomass feedstock production and provision (BFPP) system, which is the focus of this book. The next section describes the BFPP system in detail.

However, the scope of the book first needs to be defined. As mentioned before, both forestry and agriculture represent important sources of lignocellulosic biomass feedstock. The supply systems for the forestry-based material are fairly well developed as part of the pulp and paper and logging industry. It is expected that many of the operations in this system will not change even if the biomass is to be used for energy production. However, this is not true for the agricultural feedstocks such as energy grasses and crop residues. The crop residues have mostly been used for very local and immediate applications, and large-scale production of dedicated energy grasses is not yet practiced. Moreover, some of the novel energy crops may require new agricultural machinery and modified management practices. The long-distance transportation of these materials is also relatively difficult as compared to forestry material, since their bulk densities are much lower. Therefore, in our opinion, the BFPP systems for the agricultural sector require much improvement. The book, therefore, focuses primarily on the agricultural sources of biomass feedstock.

1.2 Biomass Feedstock Production and Provision

BFP is a critical subsystem of the overall bio-based energy production and utilization system. It provides the necessary materials input to the conversion process of biomass into fuel, power, and value-added products. This subsystem includes the operations of agronomic production of energy crops and physical processing and handling/delivery of biomass, as well as other enabling logistics. On the technical side,

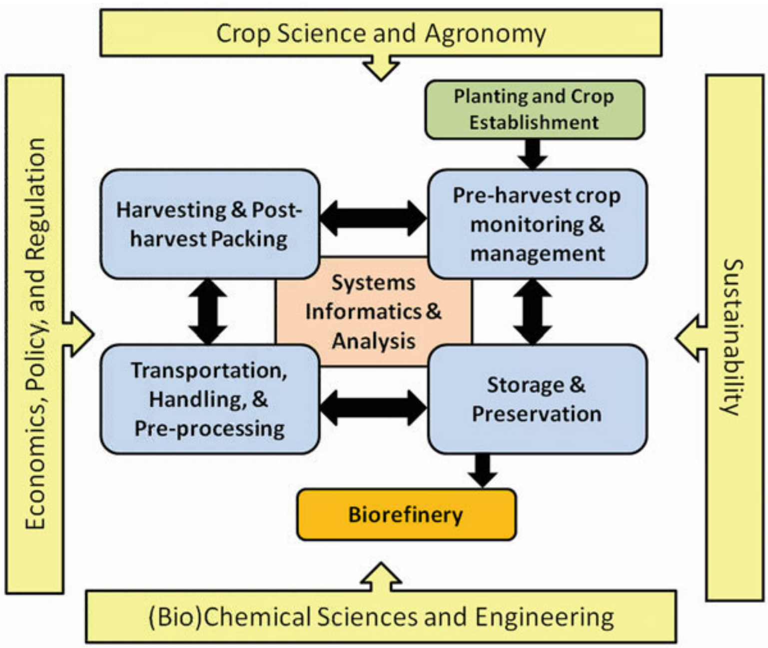

Fig. 1.1 The BFPP system consisting of four main production steps between crop production and biorefinery processing. The role of systems informatics and analysis and other extraneous factors impacting the sector are also illustrated

biological, physical, and chemical sciences need to be integrated with engineering and technology to ensure effective and efficient production of biomass feedstock. Some preliminary studies showed that feedstock supply costs including farming and delivery are up to 35–50 % of the delivered cost of bioethanol [15]. Therefore, the importance of biomass feedstock supply in the biofuels value chain is evident.

The BFPP system is shown schematically in Fig. 1.1. It can be considered as consisting of five different tasks, each representing a distinct phase in converting standing crop into biorefinery feedstock: preharvest crop management and monitoring, harvesting and handling, transportation, storage, and preprocessing. On the upstream side, the BFPP system interfaces with agronomy for crop selection, establishment, and growth. On the downstream side, the BFPP system connects with the biorefinery or bioprocessing facility that puts quantity, form, and quality constraints. These tasks are briefly summarized below:

- Agronomy: This task includes farming operations conducted prior to harvesting, including crop selection, soil preparation, planting, cultivation, fertilization, weeding, and irrigation and power. The emphasis is on developing the best management practices, which may need to be optimized for some novel energy crops.
- Preharvest crop monitoring: This task includes precision agriculture through remote sensing techniques by using tools such as cameras and sensors mounted on towers, mobile devices, or satellites. These remote sensing methods provide near-real-time

critical insights into the crop growth properties, such as salinity, nutrient status, stress levels, and yield. These insights can then be used to provide site-specific crop management strategies such as fertilization, irrigation, and weeding.

- Harvesting: Harvesting converts an energy crop in the field into feedstock material. It is considered a vital operation during the production of biomass feedstock. The efficiency of the harvester in maximizing the biomass collection is very important. A typical harvesting system can include functions such as cutting, conditioning, chopping, baling, and wrapping. Different configurations, such as self-propelled against pull type or one-pass against multiple-pass, can be used depending on the type of feedstock and equipment performance.
- Transportation: This task includes the conveyance of the biomass feedstock within the farm (short distance) as well as from farm to biorefinery or a central storage facility (long distance). Different modes of transportation include truck, rail, pipeline, barge, or a combination of these. Transportation is an unavoidable and essential task and has been identified as the major cost contributor in the overall system. The costs and energy consumption depend on crop type, bulk density, particle size, densification levels, transportation mode, and infrastructure availability. All of these must be studied to achieve maximum efficiency.
- Storage: This task aims to preserve biomass using processes that minimize total quantity and quality loss as well as biomass recalcitrance. Storage task includes on-farm open or covered storage as well as ensilage and dedicated storage such as a central/satellite storage facility that is typically covered and enclosed from all sides. Storage is important because improper storage can result in total dry matter loss, microbial deterioration, generation of chemicals inhibitory to conversion, and even combustion of the biomass. The benefits of high production yields and economical conversion to fuel will be nullified if suitable storage procedures cannot be developed to interface between the two.
- Preprocessing: Apart from the four major tasks listed above, various processing operations can be performed on the biomass as a part of these tasks. For example, drying operation is often a subtask in biomass storage [16]. Also included in this category are chemical treatments for long-term preservation of biomass or for preliminary breakdown of cellular wall structures as a precursor to biorefining, compacting or cutting of biomass for moisture removal, and biomass densification to optimize materials handling and increase vehicle transport payloads [17]. Milling has also been proposed as a potential pretreatment option.
- Biorefinery: The biorefinery utilizes the biomass feedstock made available by the preceding tasks. The feedstock may be used to produce fuel, heat, power, and/or value-added products. Each of these desired end products requires different processing routes, which may govern the optimal scale of the biorefinery. It may also impact the quantity and quality constraints of biomass that is delivered to the biorefinery.

These operations are impacted by knowledge and developments in crop sciences, chemical and biochemical sciences, chemical engineering, economics, law, regulation, policy, and sustainability. Figure 1.1 also shows these extraneous factors. In the next section, we describe a typical BFPP system that may be implemented based on the current knowledge and understanding. This description is based along the lines of different tasks described above.

1.3 Existing Biomass Feedstock Production Systems and Practices

Presently, there is very little large-scale cultivation and production of dedicated energy crops such as perennial grasses supporting lignocellulosic biorefineries. As a result, most of the lignocellulosic biorefineries are using agricultural residues such as corn stover and wheat straw as feedstock. Moreover, these biorefineries are not operating at very large scales, since many have been developed at pilot or demonstration scale to validate the conversion processes. Consequently, a commercial-scale lignocellulosic BFPP system does not exist. However, we have described here a typical production and provision system that one might expect given the currently available technologies and understanding. The system is schematically depicted in Fig. 1.2.

1.3.1 Cultivation and Crop Management

For agricultural residues as feedstocks, the agronomic practices developed primarily to optimize the yield and quality of the main crop such as corn, wheat, and rice will be used. These agronomic practices related to cultivation, irrigation, fertilization, and management have improved over the years. These are extensively covered in past literature and, therefore, are not discussed here.

The cultivation of dedicated energy crops such as Miscanthus and switchgrass (*Panicum virgatum*) has been limited and mostly on test plots with the primary purpose of conducting agronomic research. Cultivation of switchgrass is from seeds and, therefore, existing seeding equipment can be used. For Miscanthus, the practice depends on the particular hybrid being used. *Miscanthus × giganteus*, one of the hybrids that have been proposed as a potential feedstock due to its various benefits, does not produce seeds. Therefore, it is cultivated through rhizomes. The equipment for Miscanthus rhizome planting does not exist, so often potato planters are used.

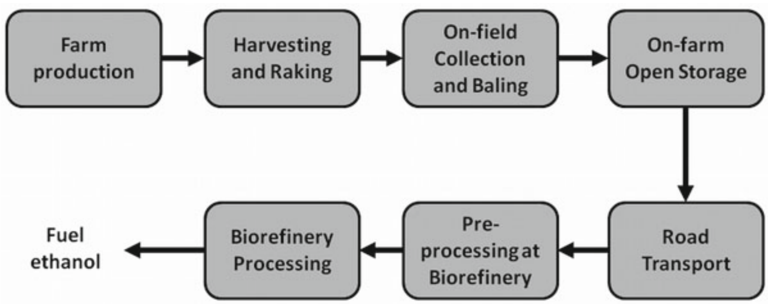

Fig. 1.2 Typical BFP system expected to be currently practiced in agriculture based on the available technology

Even for digging up the rhizomes of mature plants for propagation, a potato harvester is often used. The seeding for switchgrass and rhizome planting for Miscanthus will typically be done in late spring or early summer when possibility of frost is minimal.

The irrigation and fertilization practices for dedicated energy crops have not yet been optimized. Although these crops can produce good yields even without fertilization, some fertilization will be done, especially in the first year to improve yield. For example, the application of nitrogen fertilizer on switchgrass monoculture increased the yield significantly [18, 19]. The impact of fertilization on Miscanthus yield has been found to be less pronounced. The application of pesticides and herbicides may also be done, and the optimal application rates are being currently investigated.

A major issue for these perennial crops is survival during winter, also known as overwintering, especially in the temperate and cold regions. Excessive cold may damage the seed and rhizome, which may lead to lack of emergence during the next growing season. In the first season itself, some seeds and rhizome may fail to emerge. Consequently, some reseeding will be required at the beginning of the second and possibly third growing season.

1.3.2 Harvesting, Packing, and Handling

The crop residue is generated during the harvesting of the primary crop, such as corn and wheat. The residue left on the field after the primary harvesting operation is over will be collected and baled. The equipment and associated technology are well developed and available. Crop residue, if left on the field, enriches soil nutrients and moisture and reduces soil and water erosion. Therefore, the fraction of residue that is collected will have to be carefully decided. It has been reported in the literature that only up to 30 % of corn stover can be sustainably collected after accounting for these factors [20]. For dedicated energy grasses, the collection will depend on the type of harvesting system being employed. The two-pass collection system appears to be the one that will most often be used for energy crops. The harvester or mower will harvest the biomass crop in the first pass, while a baler will later pick it up and bale it in the second pass. The collection efficiency will be lower because all biomass cannot be picked up by the baler. Moreover, there is the possibility of soil contamination. To overcome these issues, and also to speed up the overall process, a single-pass operation is being proposed. The harvested biomass is directly sent to a baler without being dropped on the ground. This ensures that all the biomass is baled without any soil contamination. However, this technology is still at the demonstration stage. For baling, a round baler normally has a lower throughput rate and output bale density than a square baler [21]. However, it might still be used more often because it is cheaper than a square baler. Moreover, round bales shed water more readily than square bales. This means that if the bales are to be stored in the open without protection, biomass in round baled form would be better protected against rain. Another option that has been implemented, especially in Europe, is the self-propelled forage harvester (SPFH). With an SPFH, the biomass is harvested and immediately chopped into smaller particles, which are then loaded onto a wagon moving alongside the SPFH.

For the energy crops, a two-cut system has also been proposed. In this system, the crops are harvested once midway into the growing season and again at the end of the season. It has been argued that such a system will increase the total biomass output. However, studies confirming this advantage have been limited. Moreover, high moisture content of the biomass and the nutrients removed along with the biomass harvested during the first cut will be problematic. Therefore, as per the current understanding, a single-cut system will be employed.

1.3.3 Storage

The bales would normally be stored at the edge of the farm in the open. The ground may be paved or it may consist of gravel pad. It is being argued that setting up a covered storage facility on the farm may not be cost-effective given the low bulk density of the biomass. If the expected duration of the storage is long, or if the weather is not very conducive (high rainfall, stiff winds), then the bales might be covered with tarpaulin. The moisture content of the material at the time of harvesting and baling may also have an impact on the storage method. The use of an SPFH for harvesting creates problems for storage because the chopped biomass cannot be stored in the open. Closed structures, such as a shed or a silo, will be required for long-term storage of chopped biomass. An SPFH, therefore, may be preferred only in cases in which the chopped biomass is directly delivered to the conversion facility. The idea of storing of biomass at dedicated storage facilities is not widely accepted at this stage. There is, therefore, an increasing interest in incorporating some form of preprocessing along with storage at these facilities. These are often referred to as storage and preprocessing depots or centralized storage and preprocessing facilities. However, such facilities do not currently exist, even for agricultural residues.

1.3.4 Transportation and Preprocessing

The transportation of biomass would be by road using trucks and trailers. It is believed that the maximum feasible collection distance of biomass for a biorefinery would be about 150–200 km. Beyond this distance, the cost and energy consumption associated with transportation will increase substantially. Therefore, truck transportation would be most appropriate because it provides the necessary flexibility. This flexibility is essential since it allows collection of biomass from diverse locations, in relatively smaller quantities, and its delivery at the biorefinery. There is some concern about the possible traffic congestion at the biorefinery site given the number of truck deliveries required every day. This might have implications on the site selection as well as the size of the biorefinery.

1.3.5 Processing

The biomass processing and conversion facilities will typically have a buffer storage containing biomass sufficient to meet the demand for 7–10 days. The biomass received from the farms or removed from the buffer storage will first be ground to achieve the desired particle size. The optimal particle size is not yet known, and it will depend on the processing option selected. However, in general, a smaller particle size will improve the conversion efficiency by increasing the total surface area for thermal, chemical, or enzymatic reactions. The quality parameters such as moisture and ash content are not yet standardized. Hence, these parameters often differ for different pilot- and demonstration-scale biorefineries currently operational.

1.4 Challenges in Biomass Feedstock Production

Although the tasks within the feedstock production system described above are common to most agricultural products, there are challenges specific to bioenergy crops. In general, expert knowledge about the appropriate production and provision practices is not readily available, because the bioenergy feedstock sector is relatively young with very little large-scale, commercial production. Another equally important issue is the mismatch between supply and demand. Given the year-round demand for fuel, biorefineries would require an uninterrupted supply of the feedstock. Harvesting of the energy crops, though, is typically done over a period of 2–3 months. This means that the supply system must account for intermediate storage and should do so at minimum cost and quality degradation. The biomass feedstock also has very low bulk and energy densities. The bulk density of a typical baler used for agricultural residue currently is about 25 % of the bulk density of coal. Similarly, the energy density of a typical lignocellulosic material in MJ/Mg is about 30 % of that of coal. This highlights the magnitude of the challenges in handling and provisioning the feedstock for large biorefineries. The logistical complexity of biomass production systems is further characterized by a wide distribution of sources, time- and weather-sensitive crop maturity, and competition from concurrent harvest operations. In addition to these broad challenges that pervade all stages of feedstock production, each of the stages mentioned earlier also has specific challenges that need to be addressed:

- Agronomy: For many novel energy crops, such as Miscanthus and energy cane, the establishment and management techniques are not well understood and, therefore, not optimized. This includes row spacing, plantation density, fertilization and irrigation, pest control, and maturation schedules. The selection of the appropriate energy crop for each region is also a major challenge in this area. It is a function of regional attributes such as soil, weather, and rainfall in addition to the crop properties.
- Preharvest crop monitoring: As mentioned before, precision agriculture and remote sensing operations must be used to improve crop management and the

final yield through site-specific management. However, the establishment and management of energy crops may require technologies and methods different than traditional crops. The information specific to novel energy crops, such as which biophysical property to study and which sensing method is most useful, has been lacking. The functional relationships to correlate remote sensing data with physical attributes of the crops are also not established.

- Harvesting: The dedicated energy crops can be different from most forage crops and, therefore, may require new harvesting technologies to be developed. Dedicated and crop-specific machinery, therefore, needs to be developed. The design of new equipment requires fundamental understanding of the crop properties, including morphological properties such as the distribution of vascular bundles in stems, degree of lignification, and geometric size of the stem as well as biomechanical properties such as elastic modulus, tensile stress, and shear stress. The improved understanding of the engineering properties of the novel energy crops is, therefore, very important. Different cutting mechanisms and their impact on cutting speed, energy consumption, and quality of cut needs to be quantified. This information must be used to design new harvesting equipment if necessary. The performance of existing and new equipment must be systematically quantified. Different operational practices, such as one-pass and multiple-pass, also need to be systematically compared. The impact of weather on harvesting operations will also be critical.
- Transportation: The low bulk densities create enormous challenges in handling and transportation of biomass feedstock. Size reduction and densification look promising for improving the transportation efficiency. However, they need to be systematically studied. In particular, the energy consumption associated with these operations needs to be quantified. New equipment based on fundamental understanding of the cutting and compression mechanism needs to be developed. Different modes of transport must be compared. For road and rail transportations, the standardization of transportation equipment as well as policies and regulation is also needed. Software tools for optimal management and operation of the fleet are also needed.
- Storage: Maintaining the quality of biomass during storage is critical. This is especially true if the biomass is to be used for biochemical processing, because microbial degradation can lead to substantial loss of cellulose, which is critical to biochemical conversion. A fundamental understanding of the factors impacting dry matter and quality loss needs to be developed. This will help in designing optimal storage methods. The options for preparing biomass for further processing by breaking down the biomass recalcitrance during storage must also be evaluated. Evaluation of different storage methods by performing field tests using real scale facilities is also required. For building storage facilities, there exists a trade-off between costs and quality control. Accurate biomass degradation patterns as a function of regional weather and incoming biomass quality are required. The low bulk and energy densities also increase the total storage area requirement. Apart from being cost-intensive, this creates safety issues.

- Preprocessing: Appropriate preprocessing technologies need to be developed for the novel crops such as Miscanthus, switchgrass, and energy cane. This includes new size reduction as well as densification equipment based on fundamental understanding of the feedstock properties. From an operational standpoint, the optimal locations for setting up these preprocessing facilities in the supply chain must also be determined.
- Biorefinery: The biorefinery faces a number of challenges in improving the biomass conversion efficiency. However, from the BFPP system standpoint, the feedstock quality and physical form specifications need to be standardized. These will have implications on the BFPP system design and operations. Ideally, these specifications should also consider the constraints of the BFPP system in addition to processing requirement.
- Biomass feedstock properties and characterization: The biomass feedstock properties play a crucial role in the performance of the individual tasks mentioned here. For example, moisture content impacts the efficiency of harvesting, size reduction, and storage. Similarly, bulk density impacts storage and transportation efficiencies. Systematic characterization of the biomass and the quantification of its properties are, therefore, essential. However, biomass feedstock may exhibit significant variability in these properties [22]. Standardized methods to estimate these properties for different feedstock are needed but currently lacking.

In addition to addressing these task-specific challenges, the broad system-level challenges must also be addressed. These are highly interdependent tasks with implications on upstream and downstream design decisions. We must, therefore, go beyond the optimization of the individual operations and focus on the compatibility of various tasks, which will lead to the overall optimal value chain configuration. Systems-based approaches that integrate systems informatics and analysis techniques, such as database design, simulation modeling, and optimization, must be used to develop new decision-making tools. The models should account for the inherent uncertainties in the system such as weather, yield, maturity schedule, and equipment breakdown. These tools must be made widely accessible, not only to experts but also to various other stakeholders in the system. Figure 1.1, therefore, shows the role of systems informatics and analysis as central to the complete BFPP system.

Finally, sustainability considerations will be very important. Biofuels and bioenergy in general have been proposed as more sustainable alternatives to the nonrenewable fossil fuels. However, these are highly complex systems in which the economic, environmental, social, and policy issues intersect. An example of this is the issue of indirect land use change due to biofuel production that has been intensely debated in academic as well as policy forums [8, 23]. The social implications of biofuels are especially important because the feedstock providers are farmers whose livelihoods will depend on the success of this sector. The environmental and ecological issues, such as species invasiveness, fertilization and irrigation requirements, and biodiversity maintenance, must also be considered. These challenging issues must be addressed by specifically conducting sustainability-focused assessments using a holistic approach.

1.5 Objectives and Goals of This Book

Achieving a sustainable BFPP system is paramount for the success of the emerging bioenergy sector. Engineering will play a critical role in addressing these challenges and ensuring the techno-economic feasibility of this sector. It must also integrate with the biological, physical, and chemical sciences and incorporate externalities, such as social/economic considerations, environmental impact, and policy/regulatory issues, to achieve a truly sustainable system. Tremendous progress has been made in the past few years towards achieving these objectives. New challenges have simultaneously emerged that need further investigation. It is, therefore, prudent at this time to review the current status and identify future challenges, which is the objective of this book.

Each of the chapters in the book aims to discuss different issues related to feedstock production and is purposely organized based on the different challenges identified above. The chapters have been prepared such that a reader interested in a specific topic can directly go to that chapter without having to read the preceding chapters. However, given the interdependencies of these various topics in a BFPP system, the links and impacts between different stages of the system are highlighted through cross-referencing between chapters at various places.

We have identified three different agricultural biomass feedstock options that, according to our opinion, will play an important role in the near-term future of bioenergy systems. These are switchgrass (*Panicum virgatum*), Miscanthus (*Miscanthus* × *giganteus*) as dedicated energy crops, and corn stover as agricultural residue. Significantly more data are available for these feedstocks for all stages of production and provision. However, a comprehensive summary and comparison, especially for all the feedstock production and provision stages, is lacking in the literature. This is especially true for Miscanthus and switchgrass given their relatively recent emergence as potential feedstock. We have, therefore, discussed these three feedstocks in most chapters. This serves the dual purpose of providing consistency among different chapters as well as presenting a summary of crop-specific literature across all feedstock production stages. Several other feedstock options, such as energy cane, sweet sorghum, tropical maize, and short rotation coppice, are also being discussed in the literature. These have been briefly discussed in individual chapters at appropriate places and in relation to that specific topic. It must also be noted that even though many of the field studies, experiments, and case studies discussed in the book are based in the United States, the scientific concepts, engineering designs, and recommendations reported have wider applicability, making the contents of the chapters relevant for other regions around the world as well.

Our objective for this book is to serve as an authoritative treatise on the topic of BFPP based on the current literature and understanding. We hope that it will serve as a guide to various interested stakeholders in the bioenergy sector such as engineers (agricultural, chemical, mechanical, civil), agronomists, academic and industrial researchers, policy makers, bioenergy industries/businesses, farmers, and farm consultants. In addition to this, we also hope that the book will serve as a foundation for the undergraduate and graduate students interested in working in this area and as a reference guide for instructors teaching courses in this area.

1.6 Summary of Chapters

This chapter has provided a broad introduction to the topic of bioenergy and the importance of BFPP for a sustainable bioenergy system. The chapter discussed the important tasks within BFPP, reviewed the current status, and identified challenges in each of these tasks. System-level issues requiring solutions were also highlighted.

As highlighted earlier, biomass feedstock properties play an important role in all the tasks. Standardized methods to estimate these properties are being developed. Chapter 2 reviews these methods with particular focus on estimating properties relevant to engineering design of the BFPP system. The properties considered include bulk density, particle density, particle size, color, moisture content, ash content, heating value, and flowability. The chapter reviews the recent developments in the characterization techniques. These properties are referred to in all the subsequent chapters. Therefore, it is appropriate to discuss this topic before the specific tasks are covered.

Chapter 3 discusses the agronomy of Miscanthus and switchgrass, two of the most promising dedicated, perennial energy crops. Since these crops are relatively novel, knowledge on cultivation, establishment, and management of these crops is very limited. The chapter summarizes the important findings from studies published in the literature, including studies conducted by authors themselves, to provide useful recommendations and guidelines. This includes recommendations on seeding rates, preferred seasons, fertilization practices, irrigation practices, and more. Farmers and farm consultants who want to grow these grasses should find this information very useful.

Chapter 4 focuses on preharvest crop monitoring of the energy crops. The importance of monitoring is first discussed and the theory behind remote sensing tools as applied to agricultural crops is briefly presented. Since very little work has been done in this area specific to the novel energy crops, the authors summarize their own research in developing three different near-real-time remote sensing platforms for crop monitoring. The basic concepts of these three platforms are discussed and some preliminary results for Miscanthus and switchgrass are also presented.

In Chap. 5, the focus shifts to the harvesting of biomass to convert it into a feedstock for further operations. Engineering properties relevant to machinery design are discussed and different harvesting subsystems, such as cutting and conditioning, are described in detail. The chapter then reviews the harvesting technologies for four bioenergy crop options: energy grasses (Miscanthus and switchgrass), short rotation woody crops (willow, poplar), green crops (energy cane, sorghum, sugarcane), and agricultural crop residue (corn stover, orchard residue). The discussion in this chapter, aided by a number of illustrations, provides an excellent summary of the knowledge in this field.

Chapter 6 discusses the long-distance transportation of biomass feedstock to a biorefinery or storage facility. Preprocessing, such as baling or pelletization; size reduction, also known as comminution; and densification play a key role in deciding the efficiency of transportation operations. Therefore, the chapter provides a comprehensive summary of the different preprocessing options, their advantages, and their drawbacks. The different transportation modes are discussed and the challenges in optimizing the transportation logistics are also presented. Various challenges in biomass transportation that need to be addressed are also presented.

In Chap. 7, issues related to long-term storage of biomass are discussed. The different storage methods are first summarized and compared. Biomass properties that impact storage are then discussed. Total dry matter loss as well as quality degradation are the two important problems with long-term storage. Possible means to minimize these losses are discussed. Since storage can also be used for some preprocessing to prepare biomass for conversion, options to reduce biomass recalcitrance are presented. General guidelines that may be used while selecting a storage method are also presented.

Chapter 8 takes a holistic view of the BFPP system and summarizes the work done in applying systems informatics and analysis tool for BFPP system design and analysis. The literature at four different scales, namely, crop growth and management, on-farm production, local production and provision, and regional/national/global, is presented. Important modeling and informatics approaches are presented and their applications, along with key results, are summarized. The chapter also identifies several research gaps that need to be addressed in the future. The chapter should be highly relevant for farmers, managers, and biorefinery investors.

Chapter 9, a really unique component of the book, explores the sustainability aspect of BFPP. Contrary to all other chapters, it takes a legal and policy perspective to elaborate on sustainability of BFPP. Policy and regulatory initiatives existing or proposed in the USA, Europe, and Brazil to ensure sustainable production of biomass feedstock are summarized. In addition, private initiatives are also presented. Various complex issues related to these initiatives are identified. This chapter is highly relevant for businesses and potential investors who may be interested in ensuring the long-term sustainability of the bioenergy systems.

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