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Effect of Biomass Feedstock Chemical and Physical Properties on Energy Conversion Processes

Volume 1 - Overview

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December 1988

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SUMMARY

Pacific Northwest Laboratory has completed an initial investigation of the effects of physical and chemical properties of biomass feedstocks relative to their performance in biomass energy conversion systems. Both biochemical conversion routes (anaerobic digestion and ethanol fermentation) and thermochemical routes (combustion, pyrolysis, and gasification) were included in the study. Related processes including chemical and physical pretreatment to improve digestibility, and size and density modification processes such as milling and pelletizing were also examined.

This overview report provides background and discussion of feedstock and conversion relationships, along with recommendations for future research. The recommendations include 1) coordinate production and conversion research programs; 2) quantify the relationship between feedstock properties and conversion priorities; 3) develop a common framework for evaluating and characterizing biomass feedstocks; 4) include conversion effects as part of the criteria for selecting feedstock breeding programs; and 5) continue emphasis on multiple feedstock/conversion options for biomass energy systems.

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INTRODUCTION

Biomass has been used as a fuel since before recorded history. In pre-industrial civilizations, and for most of the industrial era, optimal utilization of biomass resources was not an issue. The resource base available was always much larger than the demand, and environmental concerns had not yet been raised. For the most part, indigenous biomass was collected from natural growth and burned, with the heat being used for space heating, cooking, and later, industrial applications. The overall efficiency of the supply and distribution system was regarded as unimportant because of the relatively immense size of the resource.

Increased industrialization has led to new issues, and new constraints have been created by a high per capita energy use, competition for resources with food and fiber production, and an increased sensitivity to preserving the natural environment. For biomass to significantly impact the nation's energy supply, attention must be focused on the optimal use of the biomass resource. Otherwise, not only will the amount of energy available from biomass be limited, but costs (economic, social, and environmental) will be greater for the energy produced.

The efficient use of biomass resources relies on the optimization of a very complex system of biomass feedstock supply, transportation, and conversion to energy products. These components of the biomass energy system are interrelated, which further complicates optimization. This report synthesizes the information gathered by Pacific Northwest Laboratory^(a) on the relationships between the feedstocks and the conversion processes. A separate volume, APPENDICES, provides a more detailed compilation of the data. Appendix A describes feedstock effects on conversion from a processing perspective and relates information reported primarily by process developers. Appendix B describes feedstock characteristics and relates those characteristics to potential effects on conversion processes from a feedstock perspective.

(a) Operated for the U.S. Department of Energy by Battelle Memorial Institute.

The effects of the physical and chemical structure of biomass are discussed in both volumes relative to conversion yields, rates, and efficiencies in a wide variety of available or experimental conversion processes. Through a better fundamental understanding of how these biomass characteristics affect the conversion process, appropriate conversion technologies can be selected for individual feedstocks.

Both biochemical conversion routes (anaerobic digestion and ethanol fermentation) and thermochemical routes (combustion, pyrolysis, and gasification) were included in the study. Related processes, including chemical and physical pretreatment to improve reactivity, and size and density modification processes, such as milling and pelletizing, were also examined.

SCOPE

The goal of this project is to strengthen the connection between production and conversion of biomass for energy uses, and the report draws together the available information dealing with feedstock property effects on conversion. We have found a general agreement that such relationships do exist and in some cases may be important as determining factors in matching feedstocks with conversion processes and in directing feedstock production efforts. At the same time, information is lacking to expand on these relationships. This lack of information was anticipated prior to the study and has been confirmed by the work reported here. Quantitative information in particular is extremely scarce, and much of the information reported here has been extrapolated from analytical models and empirical correlations.

Because of the wide range of conversion processes proposed for biomass, similar technologies are grouped into relatively broad categories. The groupings used for this investigation are shown in Figure 1.

The types of criteria selected for measuring feedstock effects are illustrated in Figure 2. These criteria are based almost entirely on the factors affecting the conversion process itself. Production and harvest considerations, while very important in determining overall process economics, were not included in the scope of this report since they are relatively independent of the conversion process. However, the distinction

FIGURE 1. Biomass Conversion Technology Categories Considered in This Report

FIGURE 2. Types of Performance Criteria Considered in the Study

between technical and economic issues is not always clear. For example, ash and moisture content have significant impacts on the delivered cost per Btu of a feedstock; on the other hand, these same factors also exert an impact on the conversion performance by affecting the flame temperature, ignitability, and feeding characteristics of the fuel. An attempt was made here to include discussions of such topics, which are both conversion- and production-related.

METHODOLOGY

The information used to prepare this report was gathered from numerous sources. Manual searches of conference proceedings and texts, discussions with other researchers, and computer-aided searches of the DOE-ENERGY and AGRICOLA databases were used to identify relevant information. In addition, the immense body of literature surrounding the thermal treatment of coal was used to "fill in the gaps." Of the more than 600 titles identified, the most relevant references are cited. Individual contributions were also made by a number of biomass researchers who shared opinions, thoughts, and unpublished data.

METHODS

The information used to prepare this report was gathered from numerous sources. Manual searches of conference proceedings and books, discussions with other researchers, and computer-aided searches of the MEDLINE and AMED databases were used to identify relevant information. In addition, the research body of literature surrounding the theory of treatment of oral was used to "fill in the gaps." Of the more than 800 titles identified, the most relevant references are cited. Individual contributions were also made by a number of clinical researchers who shared opinions, thoughts, and unpublished data.

BACKGROUND

Historically, the recovery of the solar energy stored in biomass has been a relatively simple undertaking; biomass was burned. As long as biomass was located near the point of use, and provided that the point of use was stationary (such as a stove or a boiler), this option was satisfactory. Indeed, combustion remains the single most important conversion technology for biomass.

There are limitations to the direct combustion of biomass. For example, the heat produced in a boiler or furnace cannot be readily transported over appreciable distances, and the equipment used to burn solid fuels such as biomass is generally incompatible with more conventional fuels such as oil and gas. Also, the bulk energy density of biomass is low in comparison to liquid fuels such as gasoline and ethanol, making it impractical as a fuel for vehicles. Thus, to expand the uses of biomass, a number of technologies have been proposed to convert the energy stored in biomass to an intermediate fuel form. Figure 3 illustrates the types of intermediate fuels that may be produced from biomass. As shown in the figure, each of these fuels has some characteristic that gives it an advantage over the raw biomass.

The wide range of intermediate fuels that can be produced from biomass is a primary driving force responsible for an apparent divergence of biomass

FIGURE 3. Fuel Paths Available from Biomass

conversion technology. This divergency coupled with the inter- and intra-species variability of biomass creates the need to understand the relationship between conversion and feedstock effects.

Historically, there has been little interaction between the development of biomass production/harvest technology and the development of biomass conversion processes. Where production is based in agricultural sciences, botany, and economics, conversion is rooted in chemistry and the related engineering disciplines of chemical and mechanical engineering. With few exceptions, different priorities have been established within each field. As a result, developments in one field often have had little direct relevance to progress in the other. Production research has tended to emphasize the optimization of total crop yields with a more recent emphasis on the economic and environmental issues related to converting surplus agricultural capacity to the production of energy crops. Conversion research has focused on the chemistry of products and the development of efficient and environmentally sound reactor systems. Implicit in both sets of research priorities is the assumption that "biomass is biomass."

In some instances, "crossover" work has occurred in which the relationship between biomass characteristics and conversion performance is taken into consideration. For example, the IFAS/GRI^(a) project, "Methane from Biomass and Waste," investigated the fermentability of various biomass feedstocks and concluded that those with higher percentages of cell wall components and lignin were less fermentable (Bjorndal and Moore 1986). The general trend, however, has been to spend relatively little time in understanding these relationships. This trend is a natural outcome of the great complexity of the integrated biomass production/collection/conversion system, and is probably exacerbated by the divergent intellectual foundations of the different components of the system.

To a certain extent, the lack of information is also reflective of the relatively small scale on which most biomass research is funded, which has led to a general tendency to ignore or dismiss the effect of feedstock

(a) Institute of Food and Agricultural Sciences (Florida)/Gas Research Research Institute (Chicago)

characteristics on the conversion process. Whatever the root causes of the trend, it has impeded progress in biomass energy systems development. The lack of information limits the selection criteria in plant breeding and genetic modification programs (Carlson 1978). Thus, the primary criteria for evaluating new biofuels species are production oriented, i.e., per acre yield, hardiness, and water and nutrient requirements. These are unquestionably important criteria for the selection of new species, but reactivity, ash content, volatile content, bulk density, and other chemical and physical properties of the biomass itself should not be ignored.

While feedstock effects have not gone totally unnoticed, they have usually received only passing attention. For example, Robinson (1980) provides relatively detailed information on the wide range of feedstocks and their characteristics, but does not include the effects of these characteristics in an otherwise thorough discussion of several conversion processes.

As early as 1980 there was a call for "standardized" feedstocks so that feedstock characteristics could be eliminated from the experimental uncertainty (Diebold 1980). Yet, as recently as 1985, the following statement was presented by one active research group (Nunn et al. 1985):

There have been very few systematic studies of the independent effects of biomass type...and sample dimension on the yields, compositions, and rates of production of [biomass products].

The more recent recognition of the effect that the diverse nature of biomass could have on conversion processes was the motivating force for this project and at least part of the motivation for two other important studies. T. A. Milne of the Solar Energy Research Institute (SERI) has been studying the use of standards in biomass research. This work includes the consideration of both standard feedstocks and standard analytical and reporting methods (Milne 1984). The work is continuing under the sponsorship of the International Energy Agency (IEA), with the working title of "Methods of Analysis of Biomass for Fuels and Chemicals" (Milne 1987). Other relevant work in the thermochemical area is being carried out by a team at the University of California at Davis (Ebeling, Zohns, and Jenkins 1985). In their

work on thermochemical conversion they have identified the following properties as important feedstock characteristics:

<u>Physical Properties</u>	<u>Chemical Properties</u>	<u>Mechanical Properties</u>
Moisture Content	Proximate Analysis	Size Reduction
Bulk Density	Ultimate Analysis	Bulk Densification
Particle Size	Heating Values	Physical Handling
Heat Capacity	Ash Composition	
Porosity/Permeability	Reaction Rates	
Thermal Conductivity	Ash Fusion Temperature	
Diffusion Coefficients		

Appropriate analytical methods for measurement of some of these characteristics have also been suggested (Ebeling and Jenkins 1984).

FEEDSTOCK/CONVERSION RELATIONSHIPS

The literature review conducted for this study confirmed the scarcity of research into the effects of feedstock properties on conversion. In most cases, feedstock-related effects were mentioned only briefly (usually in qualitative terms) in the conclusions or as a topic for future research. Attempts to determine the importance of feedstock parameters from published data were further hampered by the lack of consistent feedstock characterization and the difficulty of comparing results between different experimental systems. Further research will be required to begin establishing quantitative relationships between feedstocks and performance criteria in conversion.

Similar technologies were grouped into relatively broad categories at several levels, beginning with thermochemical or biochemical processes. These primary categories were then further classified into general process approaches. The simplest criterion for grouping processes was by final products. Thus, biochemical processes were divided into anaerobic digestion processes (to produce methane) and fermentation processes (to produce ethanol).

Classifying the thermochemical processes was somewhat more complicated because many of the processes yield more than one product. Nonetheless, combustion (producing heat and steam), carbonization (producing high-grade solid fuel), gasification (producing low to medium Btu gas for industrial use or upgrading to synthetic natural gas), and pyrolytic processes (primarily producing liquid fuels) were all taken as representative process types. Some discussion is also presented in Appendix A on ancillary processes such as size reduction and mechanical, chemical, and enzymatic pretreatment of biomass.

Although the exact relationship between feedstock and process varied with each type of process, some general types of relationships were identified. Feedstock effects generally can be broken down into one of three categories:

- those affecting the mechanical aspects of the conversion process, i.e., feeding, size reduction, and ash removal

- those affecting the rate of reaction
- those affecting the product and byproduct composition, distribution, or yield.

Individually, any of these types of effects can influence the suitability of a given feedstock for a given conversion process. Of the three types of effects, the most important is product composition and yield because these parameters tend to have the most direct impact on process economics.

The mechanical properties of primary importance relate to either the mechanical strength of the feedstock (which affects the amount of energy required to cut the biomass into practical-sized particles for feeding) or the quantity and quality of the ash contained in the feedstock. The latter characteristic can affect the amount of particulate emissions from combustion and gasification systems, determine the wear rate of mechanical feeding systems, and determine which reactor design should be used for optimal removal of the remaining ash from the reaction zone.

In the second category (rate-affecting parameters), such properties as intrinsic reactivity of the biomass (which may be affected by the presence of catalytic or inhibitory materials such as ash and extractives), and ultra-structural contributions to mass and heat transfer limitations can affect the rate of conversion of the biomass in both thermochemical and biochemical systems. The rate of conversion, in turn, can influence product distribution in thermochemical systems and play a role in determining process capital costs in all types of reactors. The effects of actual feedstocks on kinetics of conversion processes are probably the least well documented of all feedstock effects, although considerable material has been published on the kinetics of model compounds.

Finally, with regard to product yield and quality, the chemical nature of the feedstock appears to affect these criteria, which are important for measuring the performance of conversion systems. This category of feedstock effects includes the quantity and nature of the major structural polymers present in the feedstock (i.e., cellulose, hemicellulose, and lignin); the presence of nitrogen and its availability to microorganisms as a nutrient;

the incorporation of organic oxygen and nitrogen into liquid fuels derived from pyrolytic processes; and a host of other minor chemical contributions to conversion performance.

Tables 1 and 2 summarize most of the qualitative considerations that should be taken into account in matching feedstocks with conversion processes. The characteristics and requirements listed in these tables are generally desirable features of a feedstock selected for the given process. The rationale for these choices is presented in more detail in Volume 2.

Although few quantitative measurements of feedstock effects are available, these effects appear unlikely to have as strong an impact on conversion process economics as the production-related factors such as production efficiency, per-acre yield, or harvesting and transportation costs. This conclusion is based on the importance of feedstock cost in determining process economics, particularly in terms of cost/Btu equivalent. However, some feedstock properties have enough influence over the economics of specific processes (i.e., such as the effect of the fermentable sugar yield on ethanol production) to be of interest and may ultimately determine the suitability of a feedstock for a specific process.

TABLE 1. Impacts of Feedstock Characteristics on Thermochemical Conversion

Characteristics	General Considerations	Combustion	Partial Oxidation	Carbonization	Rapid Pyrolysis	Liquefaction
Pretreatment	Size reduction generally limited to coarse chopping.	Minimal fines production; low density materials such as straws may require baling or pelletizing.	Same as combustion.	--	Fine size reduction required; should have low specific energy requirement.	If wet milling is required, should have low fiber strength to facilitate feeding, milling.
Chemical	Low in nitrogen and sulfur; low in volatile metals.	High lignin and extractives result in high heating value; volatile compounds facilitate ignition.	Alkali in ash may increase gas yield or rate.	Low ash; low volatiles.	Lignin tends to increase char production and decrease gas yield.	Maximum hydrogen, carbon and hydrogen/carbon.
Physical	Low in moisture content; high in bulk density; low ash content.	High ash fusion temperatures.	Nonagglomerating.	Porosity and hardness retained in product.	Low ash hardness to minimize abrasion; low thermal inertia and high porosity to facilitate rapid evolution of pyrolysis products.	--

TABLE 2. Impacts of Feedstock Characteristics on Biochemical Conversion

<u>Characteristics</u>	<u>General Considerations</u>	<u>Anaerobic</u>	<u>Ethanol</u>
Pretreatment	If stored wet, steps must be taken to prevent excessive decay growth of pathogenic organisms.	--	Hydrolysis of structural carbohydrates is required for efficient conversion.
Chemical	Low lignin content; free of pesticide and herbicide residues.	C:N atom ratio near 20 is generally optimum; ash should be low in potentially toxic metals.	High in C-6 based carbohydrates; low in ash basicity if acid hydrolysis is used.
Physical	High moisture content O.K.; high porosity and liquid or permeability.	--	Fermentable substrate must be accessible at molecular and macroscopic scales.

CONCLUSIONS AND RECOMMENDATIONS

This study has led to a number of conclusions and recommendations.

CONCLUSIONS

The review of the available literature shows that the effects of biomass properties on conversion processes have not been adequately addressed. Only qualitative conclusions are possible because no quantitative data are available to establish a hierarchy of property effects. The diverse nature of the feedstock resource and the conversion processes available for use limit the discussion to general terms. However variations in feedstock properties clearly affect all conversion processes, including high-temperature, "brute force" processes such as combustion.

A number of feedstock effects on conversion processes were identified or predicted. These were divided into mechanical effects, rate-affecting parameters, and product composition and yield. Each of these effects individually can impact the suitability of a given feedstock for conversion, but the effect of product composition and yield generally is most important.

In considering the overall biomass energy system, which is composed of production, collection, transportation, distribution, conversion, and product distribution, the effects of feedstock choice on conversion performance generally do not have as much direct impact on product economics as the production efficiency or transportation costs. In general, feedstock costs are a major (if not the most significant) determinant of product cost. Practical experience has demonstrated, however, that certain feedstock properties can determine the suitability of a feedstock for a given process, regardless of economics. For example, there are no processes specifically designed for the fermentation of high-lignin feedstocks, while nonwoody (usually high moisture) feedstocks are seldom burned. In the less extreme cases, feedstock properties can influence the economics of biomass production in subtle ways, and selection of the appropriate feedstock/conversion combination may have a positive effect on the cost of using biomass. For capital-intensive

processes, where reactor costs are usually dominant, feedstock effects on reaction kinetics and energy throughput may, in fact, exert a very strong impact on economics.

RECOMMENDATIONS

As a result of this study, several specific recommendations are made with regard to future efforts:

- The coordination of Biomass Production Programs and the Conversion Programs within the U.S. Department of Energy (DOE) which has begun through this project should be continued and expanded.
- The qualitative relationships between feedstock properties and conversion effects as identified in this report should be further studied and quantified where possible to establish the relative importance of each feedstock property.
- A common basis for the evaluation of potential biomass feedstocks should be developed, which should include an agreed-upon set of parameters to be measured, a consistent set of procedures to measure the parameter values, and a consistent means of reporting the information.
- Conversion processes should be considered in the selection and selective breeding of potential feedstocks.
- Where programmatically possible, emphasis should be placed on the concept of appropriate technology in which feedstocks are matched to the conversion process that can make optimal use of the biomass. This implies continued development of a wide range of processing options in support of production research.

We have made efforts to fully describe the rationale behind each recommendation and have developed a strategy for implementation. The following material presents an analysis for each of the recommendations.

Coordination of Production and Conversion Efforts

Until very recently, there was relatively little interaction between production and conversion researchers. The root causes of this isolation are numerous and complex and primarily institutional. The need for continued interaction is supported by the findings of this report in which the complex nature of the interaction between biomass chemistry, physical properties, and conversion method is only partially discussed. Both disciplines stand to

benefit by working more closely with the other. More importantly, the relationship between the two aspects of the biomass utilization system points to potential synergistic effects that could result from closer working relationships.

Specific recommendations to promote interaction are given below:

- A multi-disciplinary workshop session should be organized to focus on the relationship between physical and chemical properties of biomass feedstocks and the conversion processes themselves.
- Informal working relationships between production researchers and conversion researchers should be encouraged. This interaction could include exchange of information, analytical services, or materials (particularly the feedstocks themselves).
- Higher priority must be given to documenting the effects of feedstock properties on conversion effects and to the use of a wider range of feedstocks in conversion studies.

The benefits to be obtained by implementing these recommendations include a greater appreciation of feedstock effects; an increased understanding of conversion processes; and a wider interest in alternative biomass feedstocks, including nonwoody feedstocks.

Quantify the Relationships Identified in This Study

While this study made considerable progress in documenting the complexity of the relationship between feedstock properties and conversion, priorities still need to be established. Since only qualitative relationships have been identified at this time, the relative importance of these effects needs to be quantified where possible to provide clearer guidance to production researchers who are selecting species for further study. Because of the relatively fundamental nature of the needed investigations, new insights into the conversion processes themselves would be expected, leading to the potential for process improvements or new conversion concepts.

Two key tasks are implied by this recommendation:

- Develop realistic predictive models of biomass conversion systems with specifically designated parameters which can be derived from measurable biomass characteristics. Then, use these models over the known range of biomass properties to determine the sensitivity of the models to each parameter.

- Coordinate the development of these models with an experimental program which can validate the models and identify other unexpected feedstock effects.

This recommendation, if implemented, would lead to a basis for prioritizing research efforts based on the relative importance of each feedstock property to be studied. This prioritization is important, given the large number of potential feedstock effects identified, the large number of conversion processes, and the relatively limited financial resources available to DOE. This recommendation notwithstanding, there is a danger that with limited resources, only the most obvious factors will be studied and the importance of more subtle factors may not be determined.

Develop a Common Basis for Evaluating and Characterizing Biomass Feedstocks

Identifying the relationship between feedstock properties and conversion processes implies that a common framework of properties can be identified and measured. For any particular species of biomass, any number of quantitative descriptors can be used to define the material. In most cases, any particular property of the biomass can likewise be measured by a number of different methods. These methods are often adapted from related disciplines (including agriculture, food science, forestry, and the pulp and paper industry, as well as the fossil fuels industry) and may have user-specific idiosyncracies which must be taken into account. Identifying a common base for the analysis of biomass feedstocks is a major research need and constitutes a major recommendation for future efforts.

Work on the development of common analytical methods and procedures should take into account the similar work being carried out by Milne (1984, 1987) and Ebeling, Zohns, and Jenkins (1985) (see Background section). However, there is no doubt that any progress in this area would represent a considerable improvement and is required for a basis of communications between production and conversion researchers. Some recommended first steps would include the following activities:

- Identify an initial hierarchy of information needs, based on existing information. This hierarchy would be based on the relative importance of the information (data) in optimizing the production-conversion relationship.

- Identify and publish applicable standard methods for determining the biomass characteristics.
- Identify a standard reporting format for the collected data. This format would include minimal data requirements and standardized units for reporting.

Eventually, a database of feedstock properties could be established that ideally would include all available analytical data, growing and harvesting conditions for each plant, and a bibliographic reference.

Implementing these recommendations would greatly facilitate the continued study of feedstock effects by making the needed characterization data available in any published report on biomass research. It can also be expected that the increased visibility of feedstock characterization data would promote a greater interest in the relationship between feedstock composition and conversion performance.

Include Conversion Effects in the Selection Criteria for Feedstock Breeding Programs

To a limited degree, certain feedstock properties (such as fermentable sugars and carbohydrate content) are already being used to guide selective breeding programs in the development of better energy crops. Additional emphasis in this area should be given to the importance of developing feedstocks with the right combination of properties. A single best biomass feedstock will not be optimum for all types of conversion processes. Therefore, specific needs of each conversion process must be considered if feedstock properties are to be optimized for the conversion process. Specification of required feedstock properties will involve interaction of the Production program managers with the Conversion program managers within DOE's Biofuels and Municipal Waste Technology Division programs to determine current process emphasis and feedstock needs. Benefits to be realized would include the potential for higher process yields and spinoffs from the improved understanding of plant genetics and biochemistry.

Continue a Programmatic Emphasis on Multiple Feedstock/Multiple Conversion Options for Biomass Energy Systems

No one feedstock is ideal for every conversion process. Characteristics that make a certain feed useful for anaerobic digestion, for example, may not be important at all in a rapid pyrolysis process. Furthermore, a diverse biomass resource base is advantageous both technically and economically. To fully utilize the maximum potential of biomass, it is important to maintain the concept of "appropriate technology." In this context, appropriate technology means matching the appropriate feedstock to the appropriate process.

Due to the number of options available to the potential industrial user of biomass, steps must be taken to improve the awareness of potential feedstock effects. An "expert system" could be created, based on the findings of this report, and readily updated to include any later information. An expert system is essentially a simple application of artificial intelligence that presents the user with a number of options and applies selection criteria to narrow the choice to one or two appropriate responses. Expert systems can deal with the qualitative type of information that has been developed here and while much remains to be learned, enough data are available to warrant the initial development of such a system.

The benefits of such a program would include the increased likelihood of industrial interest in biofuels, since uncertainties regarding operation of conversion systems ranks as a leading barrier to increased use of biomass by the industrial sector. Continuation of the multiple conversion option also helps to expand the biomass resource base by providing appropriate matches between available technology and available feedstocks.

SUMMARY

In the context of existing biofuels programs, many of the recommendations could probably be implemented with a minimum of new projects. The major benefit of implementing these recommendations is a more systematic basis for optimizing the complex series of processes involved in producing, collecting, and converting biomass to useful energy products.

Implementation should begin soon, before renewed pressure on fossil fuel resources places a renewed emphasis on establishing pilot and commercial-scale demonstrations of biomass conversion technology. Experience of the past decade has demonstrated that the political and funding pressures created by a major energy shortage often work against the reasoned development of optimized systems and in favor of the rapid development of near-commercial systems which may not incorporate state-of-the-art knowledge. Technological advances should be made while biomass is still considered a developing energy technology.

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