PLANT/CROP-BASED RENEWABLE RESOURCES 2020

A VISION TO ENHANCE U.S. ECONOMIC SECURITY THROUGH RENEWABLE PLANT/CROP-BASED RESOURCE USE

About This Vision

This strategic vision for the plant/crop-based renewables industry was developed by the broad U.S. agricultural, forestry, and chemical communities, with contributions from a wide range of individuals. A uniquely diverse set of American companies, nonprofit groups, trade associations, and academic institutions have come together for the first time to produce a shared vision of the future for this emerging industry.

The National Corn Growers Association initiated this effort through a strategic visioning workshop held in St. Louis in December, 1996. The goal of this workshop was to start crafting an industry vision that would lead us into an era where plant/crop-based renewables could serve as complementary resources to conventional feedstocks to meet our ever-growing need for chemicals, materials, and other products. This vision document broadly outlines the potential reaches of this home-grown industry into the core manufacturing capabilities of this nation. This document is also an invitation to all readers to participate in developing the technology plans that will make the vision a reality.

PLANT/CROP-BASED RENEWABLE RESOURCES 2020

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Plant/crop-based resources are defined as source material derived from a wide range of biological plant systems and processing streams in the food, feed, and fiber industries. An inherent assumption is that these resources are renewable over a short time frame, through use of annual crops, perennials, and short-rotation woody species. The U.S. has significant plant/crop-based resources, including forestry, rangeland, and a highly productive agricultural system. In the past 50 years, these resources have been largely focused toward food, feed and fiber production. Use of plant/crop resources for energy, or as basic building blocks for industrial production, has been limited because of a poor fit with the hydrocarbon processing system that has been successfully developed to utilize fossil fuels.

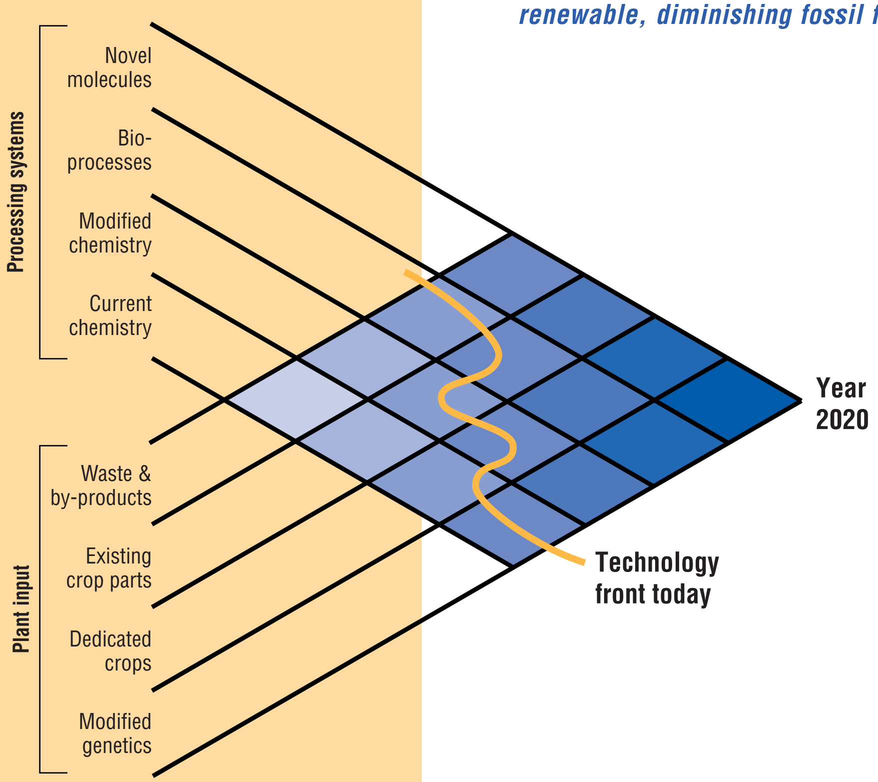
Sustained economic growth depends on having a secure supply of raw material inputs. With rapid world growth and continuing changes in consumer demands, there is a need to find additional, and preferably renewable, resources for industrial production and energy needs.

The vision is to provide continued economic growth, healthy standards of living, and strong national security through the development of plant/crop-based renewable resources that are a viable alternative to the current dependence on non-renewable, diminishing fossil fuels.

The concepts inherent in this vision do not imply that hydrocarbon processing systems must be thrown out. Rather, the need is to explore the developing "technology front" for opportunities to:

a) utilize plant/crop-based inputs in modified processing systems,
b) develop modified plant/crop production systems to provide desirable feed stocks, and
c) integrate these approaches to create optimized systems that generate a new economic platform based on the utilization of plant/crop-derived inputs.

Figure 1. This matrix creates a structure for evaluating opportunities and priority areas for research and development.



While a vision looks forward and points to future potential, it is also recognized that change must start today. Change itself is often continuous with breakthroughs occurring at infrequent intervals. Ideally, actions and goals in support of a visionary direction should allow for incremental and breakthrough types of change. Successful progress will be achieved by integrated, multidisciplinary research in a phased approach.

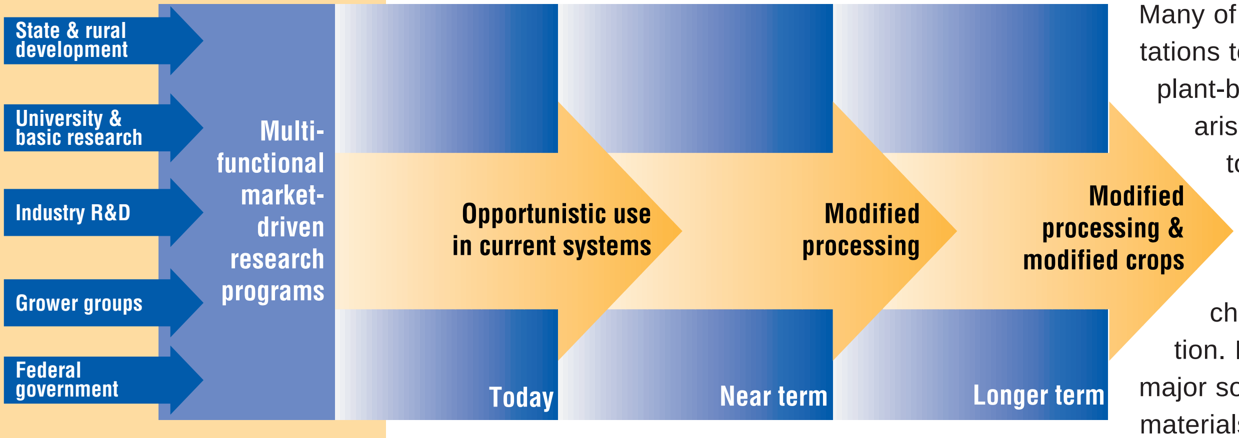


Figure 2. Successful progress will be achieved by integrated, multi-disciplinary research in phases.

Many of the current limitations to the use of plant-based materials arise from attempts to fit carbohydrate chemistry into a hydrocarbon chemistry situation. In many cases, major sources of plant materials are not even geographically suited to the locations of petrochemical processing facilities. The use of plant/crop-based resources requires the development of concepts around “alternative processing” rather than just “alternative sources” for existing processes.

In the shorter term, modified processes will allow economic use of plant/crop-based resources, while longer-term opportunities exist via the application of recent biotechnology advances.

“It is not the strongest of the species that survive, nor the most intelligent, but the one most responsive to change.”
—Charles Darwin

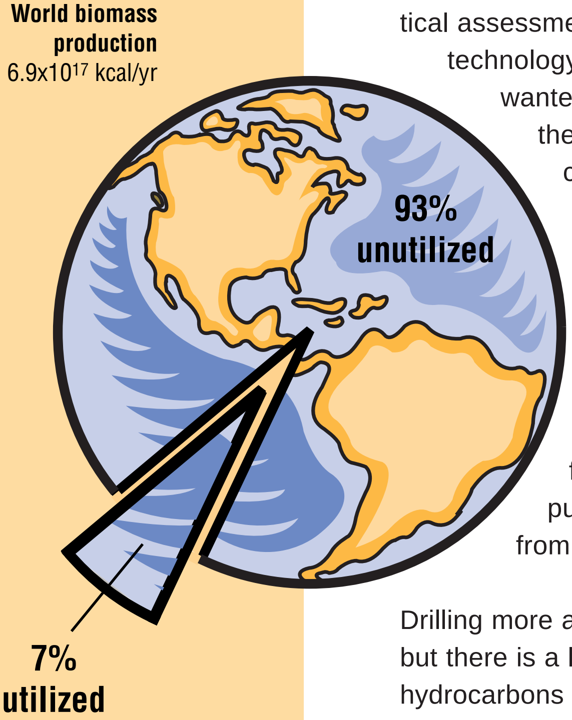
Plant/crop-based renewable resources are a strategic option to meet the growing need for industrial building blocks, and to maintain the leadership position of the U.S. into the next century. There will be economic, environmental and societal advantages from the development of this resource base. The opportunity is clear. However, it requires forward-thinking vision, integration of stakeholders, investment in new approaches, and coordination of research to generate a secure future.

This document outlines a visionary direction and states the case for using plant/crop-based renewable resources as a viable strategic option for sustained industrial growth. While directional targets and examples are provided it is recognized that there is a need to have the various stakeholders participate in a coordinated effort to identify and quantify appropriate goals, and to initiate specific projects in support of the vision.

INTRODUCTION

Imagine how the world has changed over the past 100 years: that's the magnitude of change we can expect in the next 20 to 25 years. Technological change, social structure change, human population change. It can be a terrifying picture or it can be an exciting vision.

Figure 3. Production of the world's biomass (plant-based) materials compared to the proportion utilized.



The pessimistic viewpoint is that world resources are insufficient to maintain the current exponential expansion. With no further developments to existing technology and a limited non-renewable resource pool, that may be a practical assessment. On the other hand, the optimistic viewpoint is that current technology is somewhat like the cavemen who first discovered fire. Most wanted to hide but, fortunately, there were a few brave souls who saw the potential. History has taught us that coordinated support of a clear vision can lead to resolution of gigantic problems.

Much has been written and said about the changes required to feed a world population of 10 billion or more within the next 25 years. However, much less focus has been placed on the material needs of such a growing human mass. We can reasonably assume that having food is only part of the needs equation. There will also be an exponentially growing demand for energy, transportation, housing, schools, machines, and computers, among other things. Where will all the resources come from to provide the legitimate desires of this expectant population?

Drilling more and deeper wells may provide additional hydrocarbon resources, but there is a limit to the reservoirs. Progress on more efficient use of existing hydrocarbons will continue, but perhaps with diminishing returns. Nanotechnology will allow significant miniaturization with consequent savings in materials, but some things just can't be that small. The key point is that resources are being depleted and it is futile to debate "when" they will run out, instead of looking for new paradigms to allow gradual conversion to other sources. Switching to the use of renewable resources wherever the appropriate technology is available is a more sustainable and environmentally responsible approach.

The vision for the use of plant/crop-based resources is optimistic. With the appropriate research and development of new approaches, we can discover economically viable solutions to meet the needs of a full planet. This vision sets the direction and calls for coordinated programs to identify and implement the actions required to build a renewable resource base utilizing the energy and carbon capturing systems inherent in plant systems. The challenge is significant but the opportunity is immeasurable. Humans can be responsive to change, and with the challenges ahead we must be.

What Are Plant/Crop-based Resources?

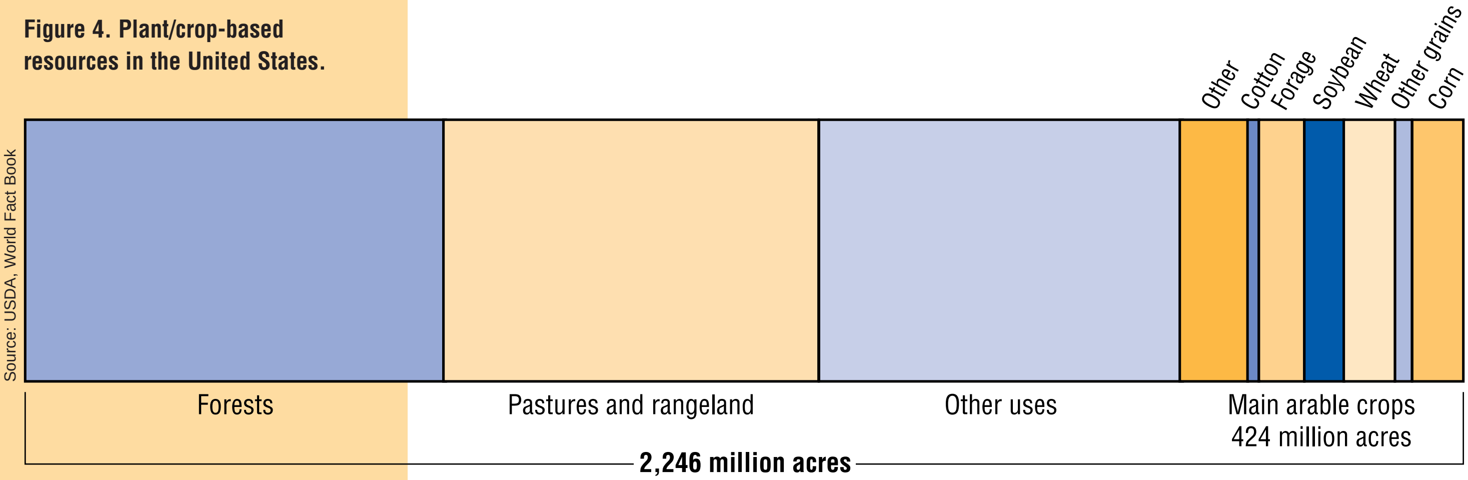
Plant/crop-based (sometimes termed bio-based) resources are defined as source material derived from a range of plant systems, primarily agricultural crops, forestry products, and processing streams in the food, feed, and fiber industries. An inherent assumption is that they are renewable over a short time frame through use of annual crops and trees, perennials, and short-rotation woody species.

While petrochemical derivatives are also originally plant based, the basic molecules are hydrocarbons. With plant/crop-based renewables, the current basic "volume" molecules are carbohydrates, lignins, and plant oils. There is also lower volumes of high-value molecules arising from secondary plant metabolites.

Another key difference is that hydrocarbons are fixed and extraction systems have been developed to manipulate them into the desired building blocks. To some extent today, plant-based renewables are also often considered as being "fixed"—taking what the plant already contains or what is left after processing. Recent advances in biotechnology promise to allow manipulation of plant constituents, and enzyme extraction systems, that could offer new economic opportunities for existing chemical product needs and for new types of intermediates and products.

The U.S. has significant plant/crop-based resources, including forestry, rangeland, and a highly productive agricultural system. In the past 50 years, these plant-based resources have been largely focused toward food, feed, and fiber production.

Figure 4. Plant/crop-based resources in the United States.



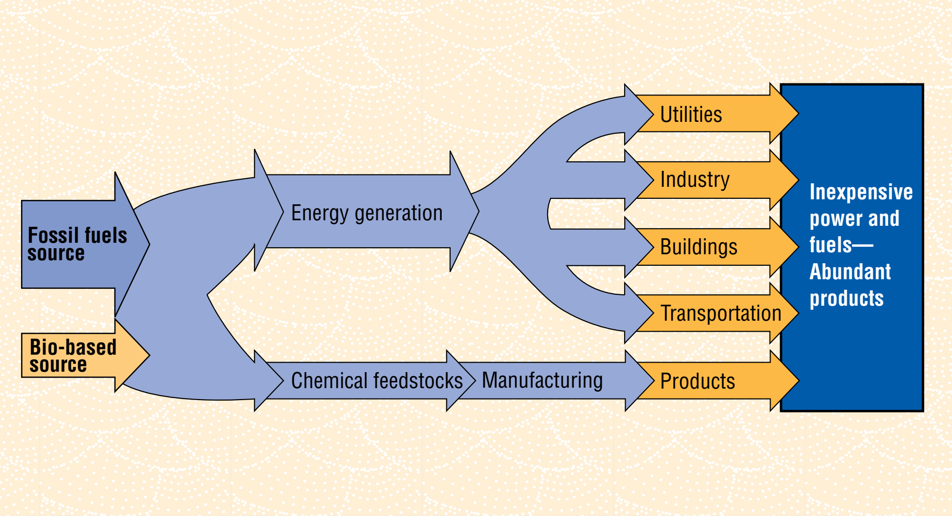
Source: USDA, World Fact Book

THE HYDROCARBON ECONOMY

We can look back on the latter part of the twentieth century and see tremendous growth in terms of economic output, especially in the developed nations and increasingly so in the developing countries. A major factor contributing to this success story was the development of the hydrocarbon economy. Since the 1920s, the extraction and utilization of fossil fuels provided the economic and standard of living benefits that we enjoy today. Many countries have become reliant on this source for both energy needs and raw material feedstocks. For example, a summary outline of energy and material flows for the U.S. is demonstrated in Figure 5.

In many ways this is a remarkable system, harvesting the energy that was once captured by plants and subsequently trapped in fossilized layers. Extensive research and development during the past 50 years has created significant value-added processes in both energy generation and in providing the basic building blocks for industry. The market economics are clearly viable and have been driven by human desires for the standard of living created by the products of the system.

Figure 5. The flows of raw materials for industrial usage in the United States.

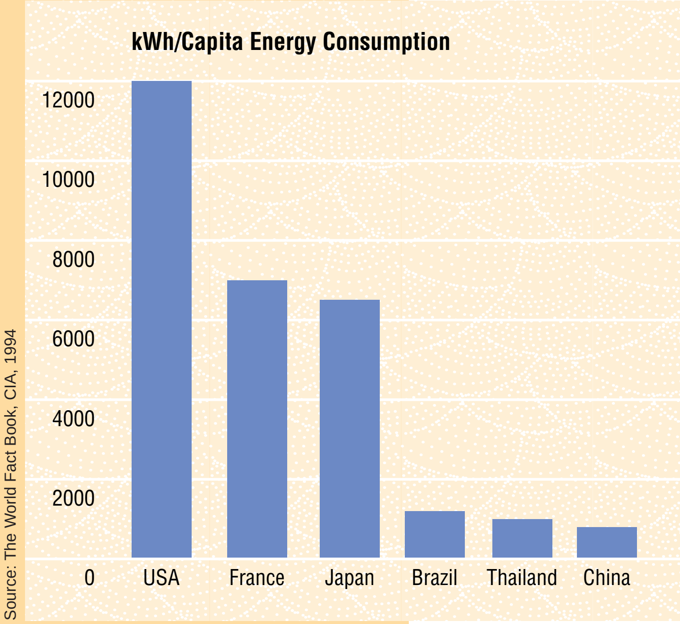


Note that current inputs to this system related to bio-based sources (mainly plant-based) are very small and account for less than 1% in energy and less than 5% in raw material inputs. As a comparison, the 1996 U.S. production of corn, soybeans, and small-grain cereals for food and feed uses amounted to 690 billion pounds. It would appear that the relative economics for use of plant-based inputs have not yet been sufficient to drive significant contributions as industrial feedstocks. On the other hand, the hydrocarbon-based economy has thrived.

Although hydrocarbons continue to provide a very successful economic platform, there are several issues related to their future use. There appear to be growing environmental concerns over the use of petrochemicals. While some of these may be valid there is, however, a much larger underlying problem. Fossil fuels are a diminishing raw material source. The use of plant/crop-based resources provides additional inputs that are renewable, and creates the opportunity for an orderly transition to a more sustainable economy.

As an example of the growing need to add additional renewable resources it is worth reviewing the energy situation. The hydrocarbon source is finite and many experts suggest that the proven and probable reserves can sustain world energy consumption at current rates for another 50 to 100 years. A potential issue is the assumption that "at current rates" equates to remaining constant. Is this a reasonable assumption given a growing population and major changes in living standards around the world?

The current per capita rates of energy consumption vary considerably around the world. Is it not reasonable to expect that the developing nations will increase their energy consumption, just as the U.S. did between 1920 and 1990? The potential problem in supply is multiplied because the developing countries tend to have large populations. For example, if energy use in China were to increase to 4000 kWh/capita (about one-third of that in the U.S. today), the incremental energy required would be about equivalent to the total energy used annually in the U.S. today.



Source: The World Fact Book, CIA, 1994

Figure 6. Current rates of energy consumption per capita vary widely around the world.

This example is not intended to be a "doomsday" statement, nor to predict the timing of fossil fuel depletion. In fact, new developments in the efficiency of hydrocarbon use will help offset the expanding demand. Nevertheless, there is an ultimate need to supplement hydrocarbon sources such that combined inputs from all sources result in a more sustainable industrial base.

New technologies require time to develop and implement. A good example is the petrochemical industry itself. In 1920, the economics of hydrocarbon feedstocks were not as attractive as they are today. Over the last 50 years, the processes have been developed to fit the fossil fuel situation. How long will it take to develop plant/crop-based systems to the same level of sophistication?

Now is the time for significant research and development on what renewable sources and novel processes might be available, and for beginning to develop selection criteria among the possible alternatives. Doing the research now does not mean that the system must change immediately. However, at some point in the future the economics of the hydrocarbon economy will fail: either through higher environmental costs or simply due to escalating prices for diminishing raw materials.

Funding the appropriate research now will allow relevant comparisons between potential sources of energy and raw materials and provide much-needed choices. In the medium-to-long term, alternatives such as plant/crop-based renewable sources may be both environmentally acceptable and economically attractive. In the shorter term, research and development may point to certain areas where plant/crop-based renewables can begin to enter the market for basic building-block molecules, thereby adding to the source base and prolonging the usefulness of the valuable fossil fuel reserves.

THE VISION FOR PLANT/CROP-BASED RENEWABLES IN 2020

The vision is to provide continued economic growth, healthy standards of living, and strong national security through the development of plant/crop-based renewable resources that are a viable alternative to the current dependence on non-renewable, diminishing fossil resources.

Implicit in this vision is the concept that plant-based resources will be phased in as increasingly important sources of raw materials for industry. The use of non-renewables may be extended with substitutions by plant-based renewables being driven by economic and environmental factors. Waiting until a crisis occurs and then trying to initiate major replacements is contrary to the vision.

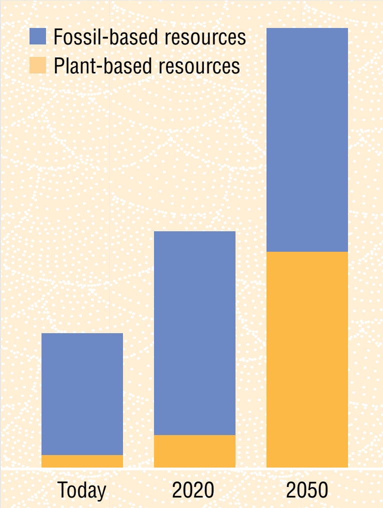


Figure 7. Vision of estimated input proportions.

Note that the vision for 2020 assumes fossil fuels will still contribute 90% of the base inputs. The addition of plant-based renewables is not an "either/or" situation, it is a necessary contribution to meet future demands. Of course, new routes for efficient processing and utilization of these plant-derived building blocks will be required. Research on these routes must start today to allow sufficient time for economic development, and to ensure the rational incorporation of best practices relative to potential environmental impacts.

The directional targets for successful progress are:

- To achieve at least 10% of basic chemical building blocks arising from plant-derived renewables by 2020, with development concepts in place by then to achieve a further increase to 50% by 2050.
- To establish plant-based (crop, forestry, processing) systems producing renewable feedstocks with efficient conversion processes to allow an economically viable and environmentally sensitive manufacturing platform for selected products by 2020. Such a production chain will demonstrate the economic viability and other potential benefits of an integrated, plant/crop-based feedstock system and highlight further areas of opportunity for commercial introductions to contribute to both domestic and export needs beyond the year 2020.
- To build collaborative partnerships among industrial stakeholders, growers, producers, academia, and federal and state governments to develop small- to large-scale commercial applications, revitalizing the economy in rural regions and providing improved integration along the value-added processing and manufacturing chain. The distinction between processing food, feed, and fiber and manufacturing basic materials will begin to disappear.

Research and development projects that provide detailed goals and objectives in support of these directional targets should receive priority for funding.

PLANT/CROP-BASED RESOURCES AS FEEDSTOCKS: CURRENT STATUS

SITUATION ANALYSIS

Hydrocarbons have become a mainstay of modern living through provision of energy and building blocks for clothing, plastics, oils, paints, dyes, pharmaceuticals, and so on. Petroleum-based plastics increased 400% between 1970 and 1990 and have gradually replaced glass, metals and even paper.

Plant/crop-based resources are not effectively used today for reasons that may include lack of utility, poor quality, variable supply, or high cost. The following sections address actions needed to drive and increase interest in using plant/crop-based renewables.

UTILITY

Although the total quantity consumed is low, plant-based materials are currently used for a wide variety of chemicals, ranging from paints to adhesives to lubricants. Soybeans have been a traditional source of vegetable oils, and more recent genetic advances have allowed the production of specialty oils for particular lubricant markets. Also, in recent years the use of soybean-derived ink has become relatively common.

For some chemicals, such as ethanol, sorbitol, cellulose, citric acid, natural rubber, most amino acids, and all proteins, plant-based systems are the major sources.

In terms of quantities of plant material used, wood for paper and fiberboard products is by far the largest segment.

Inputs	**Million tons used per year**	**Uses**
Wood	80.9	Paper, paperboard, lignocellulose composites
Industrial starch	3.0	Adhesives, polymers, resins
Vegetable oils	1.0	Surfactants, inks, paints, resins
Natural rubber	1.0	Tires, household goods
Wood extractives	0.9	Oils, gums
Cellulose	0.5	Textile fibers, polymers
Lignin	0.2	Adhesives, tanning, vanillin

Source: The Carbohydrate Economy, D. Morris and D. Ahmed, 1992

The majority of cases involved use plant-based material in an original molecular state. Complex molecules such as lignocellulose, vegetable oils, and rubber are used as such with limited chemical modification. This is in contrast to the petrochemical industry, which has developed the chemistry necessary to break down hydrocarbons into a few simple molecules (such as methane, propylene, etc). These building blocks are then used to chemically synthesize desired complex molecules.

In a few cases, plant/crop material is broken down to provide a different basic molecule. Examples include the expanded production of high-fructose corn syrup and the fermentation of corn starch to produce fuel ethanol.

These examples demonstrate that plant-derived materials do have utility, either as native complex molecules or in some cases via modification during processing. Additionally, the utility is not just for highly specialized molecules (e.g., medicinal), but can encompass larger volume intermediates and products.

SUPPLY AND QUALITY

Plant systems are geographically dispersed and encounter diverse edaphic and weather conditions, resulting in variations in supply and quality. Forest and agricultural systems have been developed to manage such vagaries with a resulting narrower range of variation in supply compared to natural wild vegetation.

General biomass production from plants is plentiful but its use has been limited due to the lack of economical chemical conversion technologies. Plant biomass tends to be “structural” material, often high in lignin and hemicellulose, which contribute to difficulties in chemical manipulation. New developments such as fast pyrolysis may allow opportunities for extraction of low molecular weight products. Additional improvements in separations technology would also help drive these. Sources of biomass could be fast-growing woody species (e.g., poplar, eucalyptus), field/range crops (e.g., selected grasses, alfalfa), and other specially bred plant species.

Other potential sources of biomass supply are current crops grown for food or feed (e.g., corn, soybeans, wheat, sorghum). In every case, only a portion of these crops is harvested. Typically the harvested portion is around one-half of the plant material available. Just for these four crops, there is an estimated average of 2600 lb/acre on a dry matter basis left in the field, providing a total of over 520 billion pounds of dry matter. While a portion of this must be retained for soil structure and to prevent erosion, the majority could be removed and used as feedstocks if appropriate, cost-effective handling systems and processing technology were available.

A major issue to be addressed in supply relates to the intent of the original production and how that is to be managed. Today, trees are grown for wood and pulp, crops are grown for food, feed, or fiber, and have not been well optimized for multiple uses. Evaluations of input costs have been based on plant/crop inputs from non-optimized (as raw materials) plant production systems, and thus carry an up-front economic penalty.

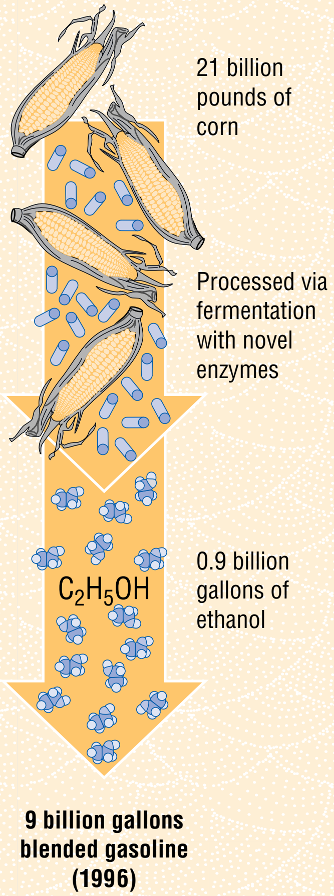


Figure 8. **Chemical conversion of starch to ethanol is difficult and too costly. When microbial enzymes are used, the process becomes more economically viable. This example also demonstrates that new possibilities might exist through novel enzyme-driven processes.**

Some proponents of increased use of plant-based renewables point to the many acres of so-called marginal land (low unit biomass production), and suggest that those acres should be the source of materials for feedstocks. Marginal land is called marginal for a reason. If economic comparisons are to be made using plant production levels from marginal land, it is difficult to envision why such a system alone would be economically viable.

Currently low-input, low-output plant production is generally not profitable for the farmer, does not support the rural community (via service needs), and may not provide lower unit cost feedstock for the processor. Moreover, the output is often variable in both quantity and quality. The ultimate products from such a system are likely to carry high unit costs and to severely limit the economic viability of the whole chain. Additionally, because low-output production requires many more acres, the unit impact on the environment is often much greater than from a more intensive system.

A Simplified Analysis of Hypothetical Production on Marginal Versus Good Croplands

To estimate dry matter output on marginal lands versus good lands, using corn, let's assume a yield of 35 bushels per acre on marginal lands. This is equivalent to the typical yield historically obtained before modern agricultural practices became widespread. If 55 percent of the crop is harvested and moisture content is 18 percent, 2,922 pounds of dry matter (grain and residues) would be obtained per acre.

On good croplands, let's assume increased usage levels if crops are grown for more than just food and feed. The current average of 120 bushels per acre yield might grow to 200 bushels per acre. If 55 percent of the crop is harvested and moisture content is again 18 percent, 16,698 pounds of dry matter will be obtained.

To estimate the anticipated economic return using these yields, it is necessary to adjust the fertilizer, chemicals, and application levels for marginal lands for economic feasibility. Let's assume favorable conditions that allow using only half the typical input requirements. The resulting variable costs are:

	Good land	Marginal land
Seed	22.38	22.38 same seed required
Fertilizer	43.47	21.74 use only half the amount on marginal land
Chemicals	24.63	12.31 use only half the amount
Application	8.27	4.13 use only half the amount
Fuel	11.05	11.05 same cultivation and harvesting
Repairs	12.74	12.74
Labor	6.05	6.05
Total variable	128.59	90.40

If we assume the grain price to be $2.60 per bushel, net income would be $391.00 per acre for good land (200 bu x $2.60=$520, minus $128.59 variable costs=$391.00) or $183.00 if yields remain at the average (120 bushels per acre) level, as opposed to 60 cents per acre for marginal lands (35 bu x $2.60=$91.00, minus $90.40 variable costs=$.60).

This explains why cultivating marginal land can not return a profit, whether used for industrial feedstocks or food, feed, or fiber. To effect major change, we need to consider optimized production systems for good lands in addition to making marginal lands more productive.

This is not to say that some land not well-used today could not be better used, nor that some plant varieties will be developed to better utilize such conditions. For major driving forces we need to consider optimized production systems, in addition to making marginal lands more productive.

There is a need to better understand the implications of using highly productive land as a resource for plant/crop-based renewable raw materials: either the whole crop, or portions not used for food or feed production. This would also help address the issues of quantity and quality variation.

The 1996 Farm Bill promoted efficient production by allowing changes in agricultural production decision-making. Farmers will grow crops based more on market forces than previously. How will this impact the potential for plant-based feedstocks? For example, a farmer may make a decision based on the projected supply-demand for ethanol compared to that for vegetable oils! The first choice is "corn" or "soybeans," the next choice is "what variety" (if corn, then select high starch for ethanol or high oil for feeding), the following choice is what level of input-output to use, and so on through which field and whether to use precision application.

Successful developments toward the vision of plant/crop-based renewables resources will extend these decisions: food or feed? feed or feedstocks? oil or starch? fiber or sugars? pharmaceuticals or polymers? The implications of such supply- and demand-driven decisions require more detailed investigation than has been devoted to this subject to date.

COST OF PLANT/CROP-BASED RAW MATERIALS TODAY

The cost of raw materials is probably the most common objection raised regarding the use of plant/crop-based renewables. The critics say it is not economical to use such inputs compared to hydrocarbons. Industrial production is driven by high-volume, low-cost raw materials. Plant materials, such as lignin or starch, can also be high-volume, low-cost materials and could compete on a commodity basis if the appropriate systems were developed.

The types of cost comparisons that have been done historically showed that plant-based materials were not particularly well-suited to the economics of the petrochemical industry, but in cases where cost was similar, the portion of material derived from plants increased significantly:

Product	**Production**	**Conventional**	**Plant Derived**	**Plant Derived**
	Million tons	**Cost $/lb**	**Cost $/lb**	**%**
Furfural	0.3	0.75	0.78	97.0
Adhesives	5.0	1.65	1.40	40.0
Fatty acids	2.5	0.46	0.33	40.0
Surfactants	3.5	0.45	0.45	35.0
Acetic acid	2.3	0.33	0.35	17.5
Plasticizers	0.8	1.50	2.50	15.0
Carbon black	1.5	0.50	0.45	12.0
Detergents	12.6	1.10	1.75	11.0
Pigments	15.5	2.00	5.80	6.0
Dyes	4.5	12.00	21.00	6.0
Wall paints	7.8	0.50	1.20	3.5
Inks	3.5	2.00	2.50	3.5
Special paints	2.4	0.80	1.75	2.0
Plastics	30.0	0.50	2.00	1.8

The real issue is perhaps one of cost of conversion to “force fit” plant-derived materials into a manufacturing system that requires a different chemical strategy. In many ways the comparison is an apples-and-oranges situation. There is a need to avoid the conflict of “either/or” and explore what opportunities can be developed to use the best of both sources of raw materials.

Plant/crop-based renewables are really not alternative sources. They are additional sources of materials for use as industrial feedstocks. The “alternative” is in process issues.

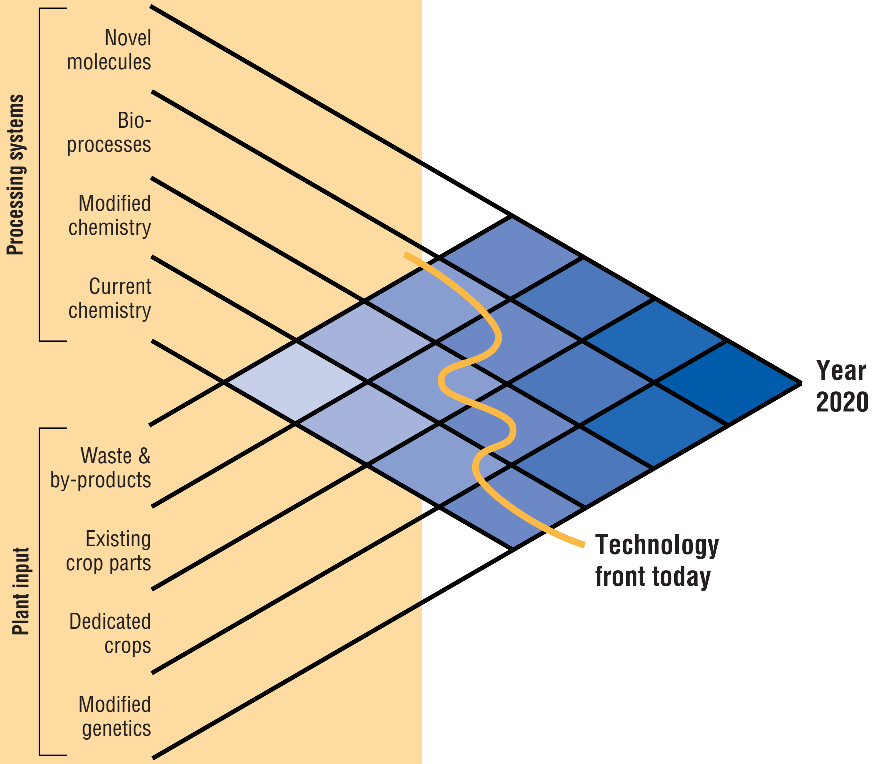
Cost limitations appear not to concern raw material cost, but rather cost associated with processing. This is really an “available technology” issue. With further development of new thermal, chemical, and biological processes, there are opportunities to expand the use of plant-based renewables in economically viable systems.

Plant/Crop-Based Resources as Feedstocks: Looking Ahead

A Matrix for Analysis of Future Developments

Plant-based inputs may take several forms (wood, cellulose, lignin, starch, amino acids, etc.), and may be sourced from different places (biomass, crop residues, dedicated crops, crop processing by-products, etc.). In some respects, this diversity is not a good fit for an industrial system that has been developed to break down hydrocarbons into a set of simple molecules and then to rebuild these into desired products. It is more fruitful to consider the development of novel processing streams, rather than just multiple sources for the existing processing stream. Both approaches may be viable, but require analysis within the appropriate context.

Figure 9. This matrix creates a structure to begin evaluating opportunities and priority areas for research and development. Each cell in the matrix should be analyzed for technology needs and economic viability.



The "technology front" estimates where we are today, demonstrates the concept of simultaneous developments within several cells (sets of input-output conditions), and shows progress toward the future.

By evaluating the possible inputs, available technology, product-type outputs, and competitive sourcing within each matrix cell, new opportunities may be more accurately quantified. Such assessments would highlight priorities for commercial development within particular sets of actual (or assumed) conditions. Additionally, cross-cell comparisons may allow research to be focused on the areas of greatest need, based on highest potential return for any given set of conditions.

Another dimension that may be more easily understood using this matrix is that of time. Clearly, genetically modified plants that produce novel products of high value relative to the consumable end-product will be economically attractive and may offer additional benefits. However, focusing on this segment alone may result in missing shorter-term opportunities because those conditions are probably a more long-term proposition. It is useful to view the matrix in terms of "where the technology front is today," which may help sort out short-, medium-, and long-term research and development needs:

Completing assessments for each of the cells will help provide answers to where research should be focused. For example, while progress today seems to be a "front" across the segments, it is relevant to ask who is coordinating this effort along the front and across disciplines and projects? What are the directional targets and criteria for success? What mechanism allows the capture of synergy among projects along the technology front?

Is it better to focus on one aspect in any particular time-frame, or even attempt to “leap-frog” certain sets of conditions? We need to better understand the technical options and social and economic implications of various approaches. Answers to such questions will help focus limited research funds into potentially higher-return projects, and allow the technology to be implemented in a more timely manner.

In the next section, each of the cells (condition sets) will be examined briefly for current fit and future potential fit with the vision outlined for plant/crop-based renewable resources. The comments provided are examples of the status and possibilities, and are not intended to be prescriptive.

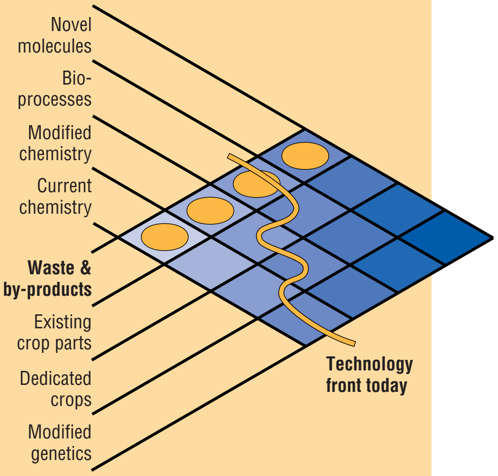


Figure 10.

SEGMENT POTENTIALS

1. WASTE STREAMS AND BY-PRODUCTS

Today this is an opportunistic segment but could become more important as new processing technologies develop.

A) Current Chemistry

The forestry industry has developed the use of by-products to a significant extent: e.g., pulping liquors converted into lignosulfonate surfactants, dimethylsulfoxide, or bark used as a source of tannin. The crop milling and crushing industry has developed many uses for by-products of commodity processing: e.g., furfural from oats, starch-derived adhesives, specialty cottonseed oils, citrates and amino acids from wet mills, etc. However, many food processing operations, such as vegetables and fruits, have not developed any particular uses that fit the existing system, and often discharge starch and sugars into the environment.

Use of plant by-products appears to be an opportunistic situation based on inherent molecules rather than any good fit with existing chemical manufacturing. Extraction and sale of inherent products may be viewed as a tactical method of reducing the cost of doing business, more so than a strategic move toward the use of plant-based resources.

B) Modified Chemistry

Woody plant material and several crop processing streams have a high content of lignocellulose and other carbohydrate materials. While the hydrocarbon industry has developed the capability to convert complex material into very discrete chemicals, the technologies needed to achieve this with plant-derived materials need to be further developed. Development of inexpensive plant-derived fermentation sugars is on the horizon. Advances in organometallic chemistry directed at converting carbohydrates into value-added chemicals are examples of the evolving new technologies that may allow expanded use of plant-based materials.

Modified chemistry has potential and may allow economic returns from plant-derived waste streams.

C) Bio-processing

Fermentation using microbes results in the production of certain molecules in a complex “soup” which may then be separated into desirable components. Bio-transformations are typically one-step processes using microbes, cells, or cell-free enzyme systems and provide opportunities to improve the utilization of waste streams and by-products. With improvements in separation technology, bio-processes are likely to be more widely used to harvest waste streams.

D) Novel Molecules

It is unlikely that this segment will become an important reality since “novel” molecules will be created due to some demand (and high value). Reliance on production from waste streams would not be the best source of materials for such products.

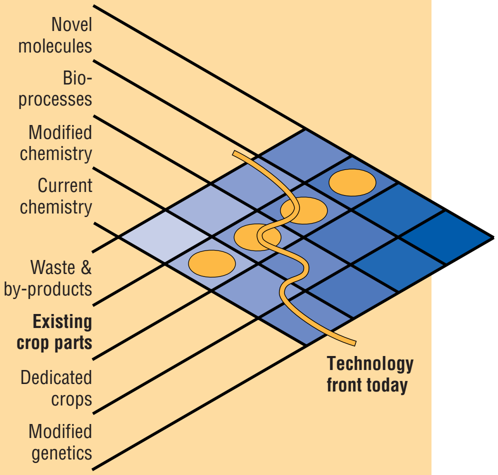


Figure 11.

2. EXISTING CROP PARTS

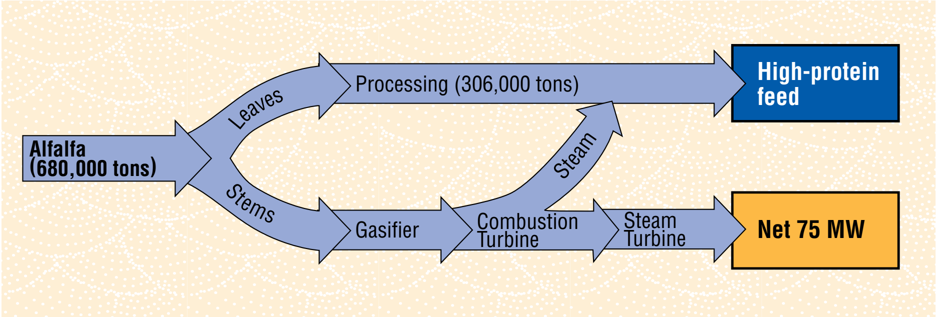
Perhaps the largest short-term opportunity to expand the use of plant-based materials.

A) Current Chemistry

Overall the chemical industry has not found plant-derived material to be of high economic value, and there are limited case-by-case uses. As discussed previously, the petrochemical industry evolved to utilize hydrocarbons, not carbohydrates or other bio-based molecules. Thus, we have what we have and further expectations should not be raised for this segment.

B) Modified Chemistry

If the plant-derived material is structural biomass then certain constituents, such as lignin and cellulosics, predominate. New techniques such as integrated combustion or organometallic chemistry may provide opportunities to better utilize this type of source. In addition to forestry sources, crop residues are a 520-billion-pound source of biomass which is not utilized today.



An example of the use of crop parts in an integrated manner is the Minnesota Agri-Power project. Some 680,000 tons of alfalfa are converted into feed with an additional net energy output.

Alternative processing routes allowed parts of an existing source to be used more effectively.

Figure 12. The Minnesota Agri-Power project uses up to 680,000 tons of alfalfa crop residues to produce 75 megawatts of electricity per day.

As new chemical technology develops there may be additional significant opportunities to use plant parts that are rich in a particular component, e.g., sugar or starch. Plant starches come in different forms such as starches from rice, potatoes, corn, and wheat. All have different properties and offer different inherent uses. More needs to be understood about the potential for such components combined with modified chemistry.

However, a key issue in this segment relates to value of developing modified chemistry versus the segment (see below) of bio-processing of crop parts. Perhaps a combination of bio-processing, new chemical processes, and advanced separation technology may provide significant opportunities.

C) Bio-processing

Again the source of plant parts for bio-processing is large and diverse, from structural biomass to specific plant constituents. There are several potential advantages in favor of bio-processing:

Advantages	Traditional Disadvantages	Recent advances include:
• Mild reaction conditions • High reaction specificity • Lower reaction energy barrier • Coupled sequential reactions • Range of energy sources • Fewer toxic by-products	• Dilute solutions • Low unit yield • Feedback inhibition • Separation/purification costs	• Improved continuous process • Advanced separations technology • Genetic modification: – Enzyme copy number – Energy source • Cell-free enzyme chemistry

Probably the most successful use of bio-processing of corn parts is in the enzymatic conversion of corn-derived glucose into high fructose corn syrup. In 1995, the production of 20 billion pounds of high fructose corn syrup used 34 billion pounds of corn.

Recent developments in this input-output segment hold significant promise for shorter-term enhancement of the use of plant-derived materials. One example is the process, developed through the collaboration of four Department of Energy laboratories, to make succinic acid via fermentation of glucose from corn. When separated, the succinate can be used to make several chemicals including butanediol, tetrahydrofuran, and pyrrolidinones. These intermediates can then be utilized to manufacture a wide assortment of products in a market segment that, today, uses one billion pounds of materials valued at $1.3 billion. This process is currently undergoing pilot-plant development.

In addition to the immediate commercial utility, this example is interesting because it demonstrates the potential for new process development that may occur when different scientific disciplines (from microbial genetics to advanced separation chemistry) are brought together to provide novel solutions. This may be an excellent model for further short-term advances in using plant-based renewables as chemical feedstocks.

D) Novel Molecules

While plant-derived inputs are relatively fixed in this segment (biomass, protein, oil, starch, etc.) the possibility to genetically modify the microbes used, or to produce specific enzymes, opens up some potential for the creation of novel molecules. Such activities are limited to small niche markets today, because the infrastructure for large-scale manufacturing is not in place. However, as the market demand for new products with particular molecular characteristics increases, then economic growth could occur from this input-output set.

Integrated technical and economic research is required along the product development chain, starting with definition of the desired product—desired characteristics—molecular structures—intermediates—enzyme technology—protein/genetic engineering—best source of plant inputs—optimization of production of selected inputs in the crop parts of choice, and so on.

As in the case of succinate, this approach can be viewed as an alternative processing route rather than just another source of feedstock inputs.

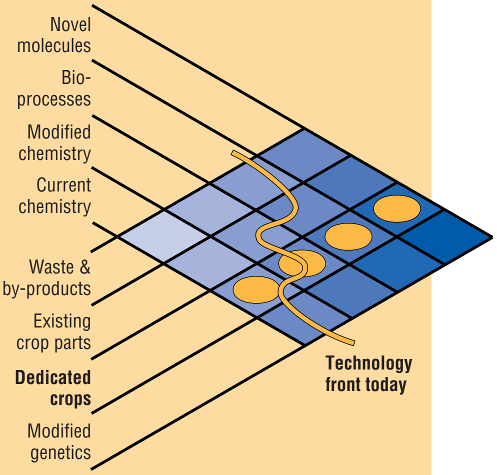


Figure 13.

3. DEDICATED CROPS

A medium-term opportunity to expand the use of plant-based materials through improvement in the source of inputs.

A) Current Chemistry

Since the chemical industry has generally not found crop parts to be of high economic value it seems unlikely that dedicated crops would be any more attractive. It may be argued that dedicated crops could lower the cost of inputs but, as mentioned previously, the real limitations may be in technology rather than input costs *per se.*

B) Modified Chemistry

The same situation exists for this input-output segment as for plant parts as inputs, with the added potential that dedicated crops may allow additional efficiencies. For example, it may be possible to more precisely align the crop type with the needs of the modified chemical process. Is biomass the best input? Or should the crop be higher or lower in particular constituents (oils, starches, proteins)? Do these help or hinder the modified process?

Another potential advantage of dedicated crops might be in relation to the logistics of supply. Depending on how the modified process is implemented, and the scale of the operations, there could be a need to draw input supplies from a surrounding area. Whether this is a current crop or use of new grass types in rangeland, the question of available supply and transport must be addressed. This is a parallel development situation with modified processing and plant supplies providing mutual support for growth.

Although several uses may exist in any one region, there may be developments of particular types in certain areas. The technology will need to fit geographic and edaphic regions. These operations may be repeated around the country as appropriate to the fit.

This alignment of new process facilities and supply would include opportunities for the economies of rural regions.

This concept of processing and production being close to supply is not unusual in industry. Petrochemical facilities are close to oil or coal supplies (indigenous or import), the orange juice processing industry is centered in the citrus-growing regions of Florida, and so on. Having plant-based inputs grown in one region and transported to another carries a large cost of transport penalty. One reason that plant-based materials have not been well integrated into traditional chemical processing may be because the hydrocarbon processing facilities tend not to be located in areas of high crop or forest production.

C) Bio-processing

Relative to inputs this segment is similar to that for modified chemistry. The difference is in how the material is processed into intermediates and/or final products. The centers of dedicated crop supply could be based around fermentation facilities just as easily as chemical facilities.

As technology develops to allow the implementation of such processing centers, there will be a need for research to determine the best alignment of inputs with the process. For example, will the dedicated crop be a single crop for a single fermentation reaction? Or will different bio-processes use different

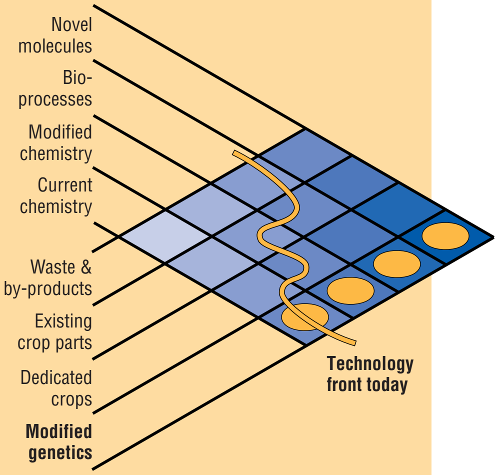


Figure 14.

parts of the crop (e.g. grain for one use and crop residue for another) in the same facility? Or will dual dedicated crops be required (e.g. a lignin bio-process that requires some sugar inputs as an energy supply)? Optimizing such alignments will be important to the economy of the operation and for the development of the region around the facility.

4. MODIFIED GENETICS

A medium- to long-term opportunity to expand the use of plant-based materials in specific ways and for specific uses. Some of these will provide outcomes that we can hardly imagine today.

Whether it's called the carbohydrate economy or something else, there will be a whole new industrial platform based on the bio-engineering of plant constituents to provide alternative renewable resources.

A) Current Chemistry

Genetic modification of plant-based inputs could likely be achieved to provide some inputs to the existing hydrocarbon processing system. However, modified plant molecules may be too valuable to degrade in a hydrocarbon system. In other words, the input technology will be able to leapfrog the processing technology. Either more complex molecules can be made directly and inserted further up the manufacturing chain, or new processing routes will be much more efficient at using the modified inputs. Benefits of the dual change will be seen in both the economy and in environmental issues.

B) Modified Chemistry

Clearly, there will be benefits from developing new process routes that optimize the type of plant/crop-input and the process. Parallel research needs to be directed at these possibilities.

In what time frame should these process research efforts be made? This can best be answered by assessing where the genetic manipulation technology is today, and how long it will be before such changes are expected in commercial situations. An overview of this situation is provided in the following section on the impact of biotechnology.

C) Bio-processing

This input-output segment is similar to that for modified chemistry. The additional factor is that microbes or enzymes or both may also be genetically altered to provide enhanced processing capabilities. There appears to be very large longer-term potential for biological engineering, where optimization can be created between input materials and the bio-process itself.

In some cases, the desired molecular building blocks may be partially synthesized in the plant material and “finished off” by bio-transformations or highly specific biological/chemical processes. The processes will be created to take account of the best method(s) for the highest efficiency, provide for optimized economics, and maximize environmental benefits.

At some point during the next 50-70 years, petrochemical processing for general high-volume molecules will begin to look somewhat sluggish, inflexible, and expensive. Research and development will be required to justify continuing to use fossil fuels for specialized uses in order to gain maximum value from the remaining limited resource.

D) Novel Molecules

In just the past 20 years, plastics have grown into a huge industry, replacing glass, porcelain, wood, and metal for many everyday uses. The marketplace continues to change, driven by the desires and expectations of consumers. Materials science continues to make significant advances, marketers continue to design novel consumer goods, and expectations rise. Who can predict what the next “plastic” will be? Yet we know there will be one.

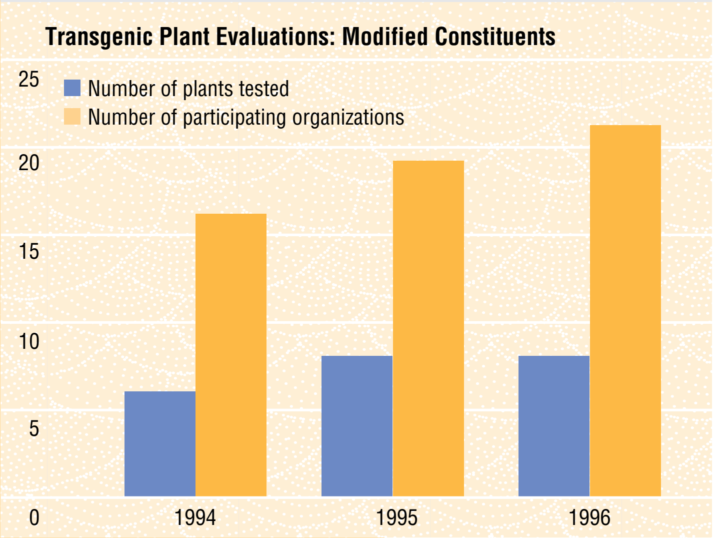
The possibilities for novel molecules to be the bases of new industrial platforms are many. The concept of marrying physical and chemical science with the ability to biologically engineer material inputs generates a new horizon. Plant-based renewable resources will be a major part of that future. Plants are highly effective factories for capturing and converting freely available solar energy. Metabolic engineering to channel that resource into desirable building blocks to support the infrastructure of society appears to be a desirable approach. It’s an area where the technology front should be advanced to explore the boundaries of possibility.

Someday, we may have solar energy collectors that contain self-replicating chloroplasts, with integrated solid-phase enzyme nanoreactors—all built into the computer controlled vehicular surfaces that in the twentieth century were called roads. In the meantime, plant-derived materials may work out just fine.

THE POTENTIAL IMPACT OF BIOTECHNOLOGY

The impact of any new area of technology may be assessed by:

- exploring the speed of change and/or the rate of introduction in recent time,
- measuring the level of interest and funding by public companies,
- evaluating patent activity and associations, and
- looking into the development pipeline to see what is making successful progress.



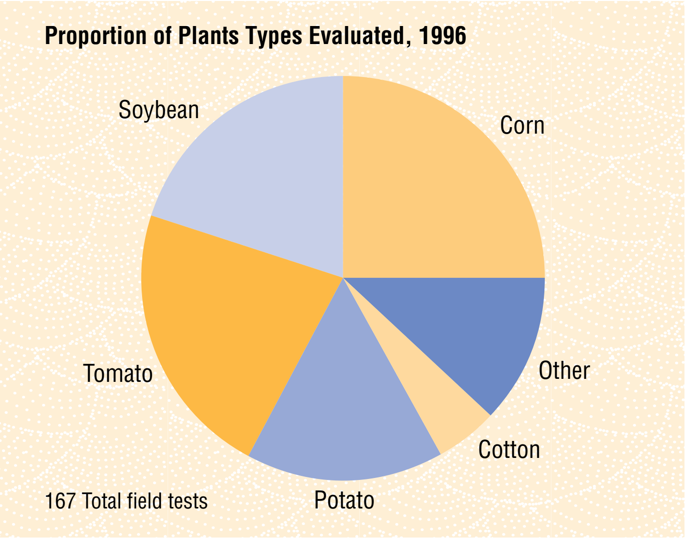


Figure 15. Much activity is underway in transgenic modification of plant constituents.

In the early 1990s, many people were very skeptical that biotechnology would make much difference in the crop world. By 1996, the commercial success of transgenic crops had been clearly demonstrated. These first successes relate to new crop protection approaches. While it is important to protect plant production from the ravages of pests and diseases, it is also important, and relevant to the vision, to understand the possibilities for modification of plant constituents.

Due to regulatory requirements, transgenic field test records are kept by the Animal and Plant Health Inspection Service. Such evaluations are for events that have been demonstrated in the laboratory and are now moving into the pipeline for development testing. Selecting the records that relate only to transgenic modification of plant constituents shows that considerable activity is underway.

The data show that several organizations are involved and that work is already underway in several crops. Among the organizations involved, the number of tests and types of modifications range from one per organization to dozens of field transgenic tests by the major players such as DuPont, Monsanto, and Pioneer Hi-Bred.

Some of the events being evaluated are related to alteration of constituents to improve nutritional quality, some are for processing characteristics, and others are for industrial or pharmaceutical uses. The types of transgenic modifications already being evaluated include:

- Carbohydrate (sugars, starch, solids) alterations,
- Oil and fatty acid modification,
- Amino acid level enhancement,
- Protein type manipulation,
- Fiber characteristic modification,
- Antibody production,
- Industrial enzyme production,
- Secondary compound manipulation (sterols, carotenoids, etc.), and
- New polymer production.

We can reasonably conclude that transgenic technology progress is significant and is moving rapidly. A new door has been opened on the opportunity for plant-based materials to provide useful sources of both molecular building blocks and more complex molecules for manufacturing industries. A specific example of this is the plant-based production of polymers for plastic manufacturing. Three genes from the bacterium *Alcaligenes eutrophus* have been inserted into the lipid synthesis pathway of plants with the result that polyhydroxybutyrate was synthesized in concentrations of up to 14%. Expression of this biodegradable thermoplastic is being developed further in soybeans, cotton, and rapeseed.

Conventional plant breeding has raised yields threefold over the past 50 years, and the selection process in those crops was for characteristics that had a good fit with food, feed, and fiber uses. Advanced plant breeding with the aid of genomic maps and transgenic techniques will provide an opportunity to further increase food and feed production with a simultaneous potential to provide plant-based materials as feedstocks for many uses.

Biotechnology already has a revolutionary impact on plant-based materials. However, use of biotechnology to alter plants to fit a hydrocarbon economy may not be the best approach. There needs to be an improved understanding of what factors along the industrial chain need to be aligned in order to take maximum advantage of future transgenic plant-based renewable resources.

WORKING APPROACH

Successful developments contributing to the vision outlined in this document will require integration of research, development, commercial process engineering, and future market understanding. Multidisciplinary projects that fit this scenario and coordination of individual projects with a common goal will be required to move the technology front forward.

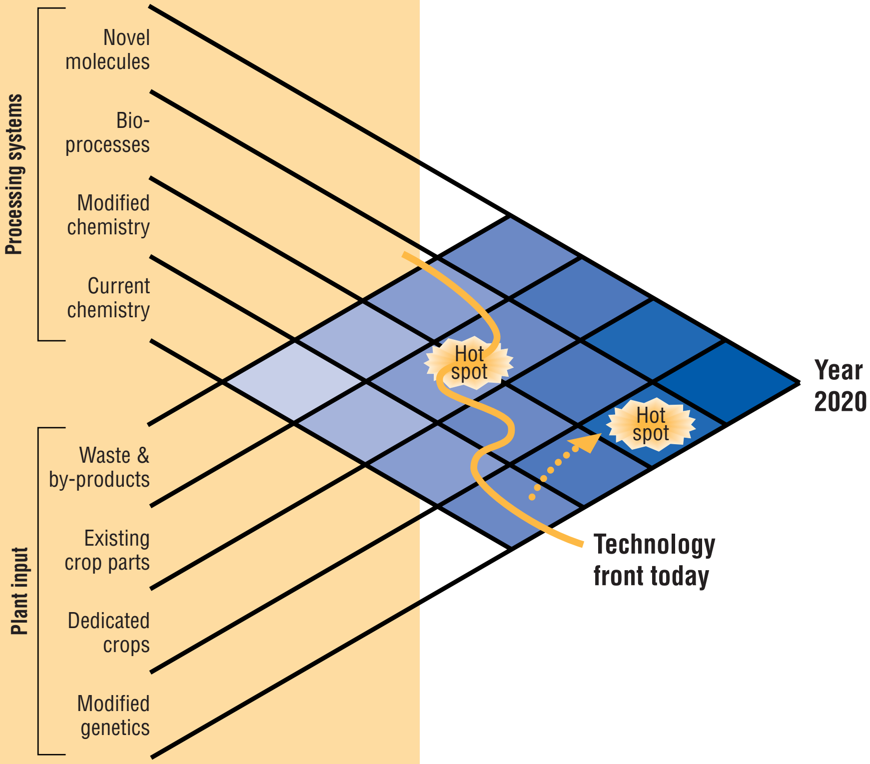


Figure 16. With the current state of knowledge, there appear to be two "hot spots" for immediate attention on the technology front.

The "hot spot" for research in use of existing crop parts with modified chemical processes, including integration of bio-processes, might be considered short-term (today to 10 years for implementation and impact). The other "hot spot" is conceptually a jump (over current hydrocarbon chemistry) to align genetically modified plants with new processes, and may be a medium- or longer-term (10 to 20 plus years to implement and impact) return for investments in research today.

If success is achieved in these areas then a solid scientific base will be available for commercial application. The additional development of dedicated crops would then be viewed as a mechanism to lower the cost of inputs to these systems, or to improve the supply situation (quantity and quality) to a growing industry.

The supply chain itself contains significant issues when viewed from a plant-based renewable resource perspective. There may be geographical advantages to certain developments that result in "centers" for processing of particular types of inputs, including access to both domestic and export markets. Identity-preserved mechanisms for transgenic crops are still evolving and the optimization of such systems for plant-based renewable resources requires further study.

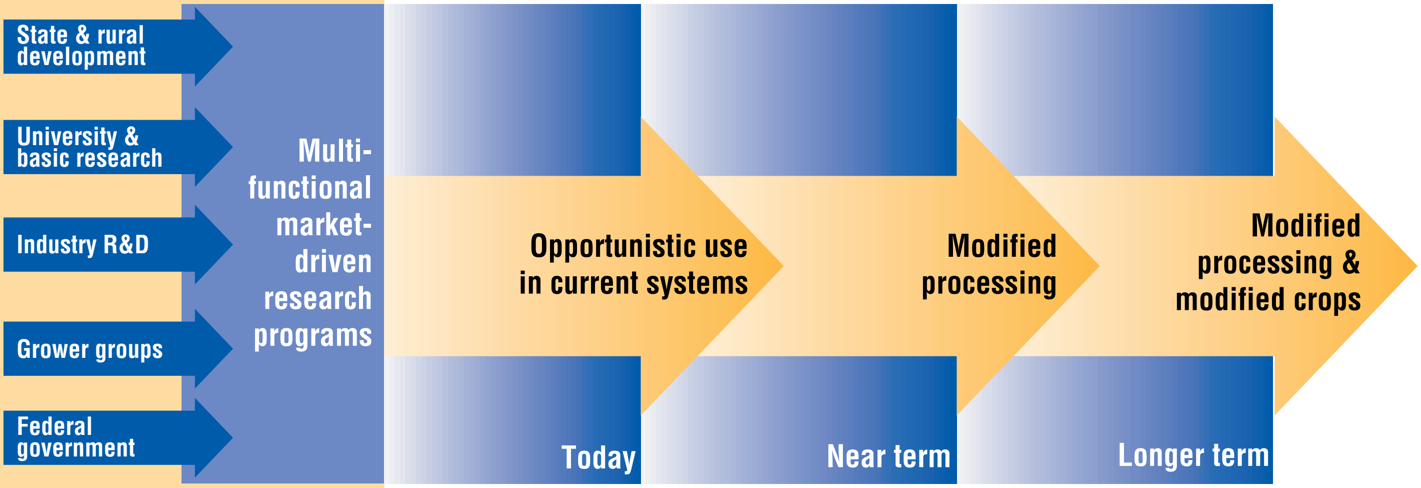
A visionary document such as this does not provide answers but rather points to the potential that can be realized from taking certain steps in various directions. The next stage is to begin a coordinated effort based on inputs from multiple stakeholders to allow the development of specific goals toward the vision. For example, a major program for developing plant/crop-based renewable resources would have specific technical goals, economic thresholds, and temporal milestones, based on proposed projects that support the visionary directional targets via research and development in one or more of the following target areas:

- optimization of biomass and/or crop-based material production to fit projected use situations,
- addressing the facilities, location, handling and delivery issues for a plant-based feedstock supply chain, including mechanisms to enhance the economy of rural regions, and
- accelerated development of new processing routes based on modified chemistry and/or bio-processes that are aligned with the utilization of plant/crop-based renewable feedstocks.

Priority would be given to projects that are supported by multi-stakeholder desires, or are multidisciplinary in nature, and that have goals with the potential to impact more than one of the above targets. The criteria for selection of funded projects should also take into account the time expectations for and magnitude of potential impact.

Plant/crop-based renewable resources are a strategic option to add to the growing need for industrial building blocks, and to maintain the leadership position of the U.S. into the twenty-first century. There can be economic, environmental, and societal advantages from the development of this base resource. The opportunity is clear. It requires forward-thinking vision, integration of stakeholders, and investment in new approaches to generate a secure future.

Figure 17. Integrated Phased Development



> *"It is not the strongest of the species that survive, nor the most intelligent, but the one most responsive to change."*
> *—Charles Darwin*

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