THE POTENTIAL OF BIOTECHNOLOGY: PROMISES, PERILS, PERPLEXITIES–A SURVEY OF IMPACTS ON RELEVANT ECONOMIC SECTORS

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ABSTRACT

Biotechnology is the latest scientific innovation that shows great economic promise but also raises many immediate as well as long term societal concerns. In the current state of the art, biotechnology has four broad areas of economic application: improving properties of plants (ag-biotech) and food (food-biotech), making industrial intermediates (industry-biotech), producing diagnostic materials and drugs from organisms (biopharmaceuticals), and mitigating pollution (environmental-biotech).

The deliverables today are only a miniscule proportion of the potential that has been mapped out. There are also environmental benefits in terms of avoided mitigation costs and intergenerational resource savings. Despite the obvious glitter and prosperity associated with biotechnology, the public and some industrial communities have been slow on the uptake. There are also pertinent concerns regarding safety, containment and segregation of transgenic produce.

Increasing the level of public awareness has to be a central objective for successful adoption of this technology, and this is a task that needs to be addressed by businesses, industry groups, professionals and regulators alike. The technology itself is powerful and transcends the bounds of the handful of industries that have adopted or experimented with biotechnology.

INTRODUCTION

In the broadest sense of the term, biotechnology implies anthropocentric interventions in the natural gene pool. This could take the simple form of favoring certain species over others, for example, by selecting the best seeds for replanting, or retaining the highest yielding animals for breeding, while slaughtering the rest. Hence, the advent of biotechnology can be traced to prehistoric times, with the first attempts to nurture only desirable plants and animals for consumption by human societies.

While early biotechnology involved creating product improvements by selection, cross-breeding and using whole organisms, the modern day version is based on the use of sub-cellular material. Recent advances in molecular biology has made it possible to transfer DNA from practically any source to create genetically modified organisms (GMOs) that display the desired functional traits (Nap et al., 2003). Thus, the process and ability to genetically transform organisms through recombinant DNA (rDNA) technology – thereby creating transgenics, or GMOs – is the theme of modern biotechnology.

Although there is amazing diversity in creation – ranging from a simple bacteria to the most complex human being – the cells of all organisms are composed of the same fundamental building material and speak the same genetic language. The astonishing ability of biotechnology to transfer genes across organisms is based on this universality of all organisms. Table 1 provides a brief glimpse of the development of biotechnology as viewed through important milestones. It is apparent that the developments vindicate the Tofflerian theory of the increasing rate of change in scientific discoveries (see, e.g., Toffler, 1971). The use of biotechnology can be broadly classified into 4 functional areas:

1. Agricultural, food and forestry products
2. Environmental uses
3. Industrial biotech
4. Biopharmaceuticals

Table 1. Important milestones in the evolution of biotechnology

Dateline	Landmarks
8000 BC	Earliest record of human intervention in genetic selection – domestication of livestock and crops (potato).
4000 BC	First active use of organisms in production – cheese and wine (China, India), beer and bread (Egypt), selective pollination of dates (Babylon).
500 BC	First antibiotic – moldy tofu used to treat boils (China).
100s	First bio-pesticide – powdered chrysanthemum (China).
1300s	Arabs use artificial insemination for improving breed stocks of horses.
1700s	Viral vaccination for smallpox (Jenner).
Early 1800s	Proteins discovered, first enzyme isolated.
Late 1800s	Darwin propounds his theory of evolution by natural selection. Mendel proposes the law of heredity - the science of genetics is launched.
Early 1900s	Bacteria used to treat sewage in Manchester, UK. The Human Growth Hormone (HGH) is discovered (Evans and Long). Penicillin is discovered as a life-saving antibiotic (Alexander Fleming). First commercial bio-pesticide (Bt) to control the corn-borer (France). Genetic material from different viruses shown to combine into a new virus.
1950s	Structure of DNA is published – start of modern genetics (Watson, Crick).
	First synthetic antibiotic is produced.
1960s	Messenger RNA (carrying developmental information in cells) is discovered. Green revolution starts with the creation of high-yielding foodgrain seeds. Genetic code is cracked (nucleotide bases determined).
1970s	First complete synthesis of a gene. Also HGH is synthesized. Recombinant DNA (rDNA) technology applied to human inherited disorder. First transgenic expressions – yeast gene in bacteria, human gene in bacteria.
1980s	Gene synthesizing machines developed. Recombinant life forms patented. Transgenics produced – mice (Ohio U.); cloned golden carp (China). DNA fingerprinting, genetic marker, recombinant vaccine, transgenic tobacco
1990s	BtCorn (pest resistant), GM cow (human milk proteins), GM yeast, GM trout. Biotech foods – FlavrSavr tomato, bST beef. Industrial bio-enzymes. Biopharma - gene therapy, recombinant antibodies used for treating cancer. Biotech crops grown worldwide – BtCorn / Cotton, Roundup Ready Soybean.
2000s	Plants as factories for therapeutic proteins (plant made pharmaceuticals). Complete map of the Human Genome published. Progress in explaining the differentiation of stem cells. High yield biotech crops in 150m acres. (Solve 3rd world nutrition problem?)

Source: BIO 2003.

The first relates to improving agronomic and environmental attributes of plants, such as yield, stress management skills, pest and disease resistance. This promises to generate huge benefits in terms of better harvests, lower production costs and less environmental damage from agrochemicals. In the food sector, the objective is to develop product attributes that have greater consumer appeal, and add nutritional value to food. The latter application somewhat overlaps those health supplements (also called *nutriceuticals*) that are derived or extracted from plants, since transgenic produce can be tailor made to supply many nutritional elements. This has given rise to the saying that there will soon be a fuzzy line between the pantry and the medicine cabinet (PEW, 2002).

The direct environmental application of biotechnology has been in developing GMOs that can mitigate pollution – transgenic bacteria that can assimilate oil spills, for instance. There are also indirect environmental benefits from most other functional uses of biotechnology: lower pesticide use through ag-biotech, faster growing trees that can sequester carbon, biopolymers, industrial bio-enzymes, are some examples.

Industrial biotech refers to using GMOs for producing industrial raw materials – for example, using transgenic bacteria to produce enzymes and acids.

Biopharmaceuticals is the fastest growing functional area since it can provide many diagnostic and therapeutic products that are beyond the scope of conventional treatment lines. A new branch of this functional area – known as plant-made-pharmaceuticals (PMPs) – appears to have great promise. Plants are extraordinary factories that have the ability to produce complex proteins, given the appropriate genetic signals. Growing therapeutic proteins in transgenic plants is the new technology for producing pharmaceuticals, and provides a cleaner, cheaper and more stable alternative to cell culture and fermentation (for example, producing insulin in corn, as opposed to porcine, bovine or human tissue).

There is a rigorous system of multi-agency – USDA, EPA, FDA – checks and approvals of biotechnology products in the US. This process takes place over multiple-stages – with oversight continuing through the stages of discovery, development, testing, clinical/ consumer trials and marketing. The only current lacuna appears to be in post-market oversight – a critical area for measuring the long term impacts of GM products in enduse consumption, and use as productive factors, as well as in ensuring their safe handling and disposal (Taylor and Tick, 2003).

Despite the obvious glitter and prosperity associated with biotechnology, the public and some industrial communities have been slow on the uptake. Even after accounting for the usual rhetoric expected from activists, there are several pertinent concerns regarding the safety and containment aspects of transgenic produce. At this time, it is impossible to ascertain the complete package of impacts that an accidental leakage of GMOs can have on the ambient ecosystems. As well, it is difficult to predict the long term (unknown) health and environmental impacts of consuming GM products that are proven to be safe in the short term.

ECONOMIC IMPLICATIONS: AN EXAMPLE OF WELFARE GAINS FROM USING PLANT-BIOTECH TO COUNTER ENVIRONMENTAL STRESSES

Taking stock of the exciting scientific developments in biotechnology, the field seems to hold out tremendous economic value for society. Also, currently available applications are only a miniscule proportion of the possibilities. There are indirect benefits in terms of avoided environmental mitigation costs, as well as the intergenerational resource savings. Experts predict that biotechnology products and processes may extend average human lifespan by 10-15 years within the next 25 years. This not only adds the value of additional human productivity to society, but also the non-market value of human life.

Plants in all regions of the planet are subject to environmental stresses related to deviations from normal temperature, moisture and nutrient regimes. For the most part, these stresses are either benign or seasonal and are well tolerated. In fact, environmental stresses are sometimes beneficial, since they act as natural mechanisms for stimulating evolution. Stresses form an important part of the design toolbox of nature, forcing organisms to react and reorient, or be replaced.

Environmental stresses cause physiological and biochemical changes in plants. Just as the market price mechanism signals resource allocations in society, these changes cause resource reallocations in plants – for example, between the strategies of survival and propagation. Much of the distribution, domination and migration of plants depend on the stress management skills of individual species. The strategies of successful species are reflected in growth, reproduction, vegetative recovery and morphology, and vary from one plant species to another (Gehring and Whitham, 1995).

The most common universal stresses relate to temperature and moisture, while soil salinity is an important factor in some regions. A majority of plants can function within reasonable ranges of these factors, while some species develop great abilities to survive and reproduce under extreme weather and soil conditions. Given that natural changes to a landscape and climate is a slow process, the evolutionary mechanism in plants have historically been allowed adequate time and space for adaptation (Dunnett, Willis, Hunt, and Grime, 1998). The process of evolutionary adaptation is slow – taking place over thousands of years. However, when the stress is beyond tolerance levels and the pace of change is rapid, then plants can either lose productive abilities or get replaced by migratory species. This not only has implications for the structure, biodiversity and functional stability of ecosystems, but can also impact supply side economics where commercial species are concerned.

Moreover, environmental stresses associated with anthropogenic modifications of the atmosphere can be of greater than normal magnitudes (by evolutionary standards) and can exceed plant tolerances.

When exposed to atmospheric and soil related stresses that are beyond their adaptive abilities, plants may react with slower vegetative growths and stunted fruit and seed production. Scientists have determined that plants under environmental stress also develop weaker resistances to pests and parasites (Louda and Collinge, 1992). In economic terms this translates into one of the following 2 scenarios:

1. Lower harvestable quantities, or
2. Higher costs of production (cost of pesticides and other inputs).

Figure 1 is a diagrammatic representation of how environmental stresses can affect human societies, considering the impacts on only those plants that are economically relevant, that is, commercially grown crops, agroforestry, etc. This figure shows a schematic market with prices on the vertical axis and quantities produced / consumed on the horizontal axis. The usual $\text{DEMAND}_{\text{NORMAL}}$ and $\text{SUPPLY}_{\text{NORMAL}}$ curves result in a typical market equilibrium (at point A) generating the market clearing price P_A and quantity Q_A.

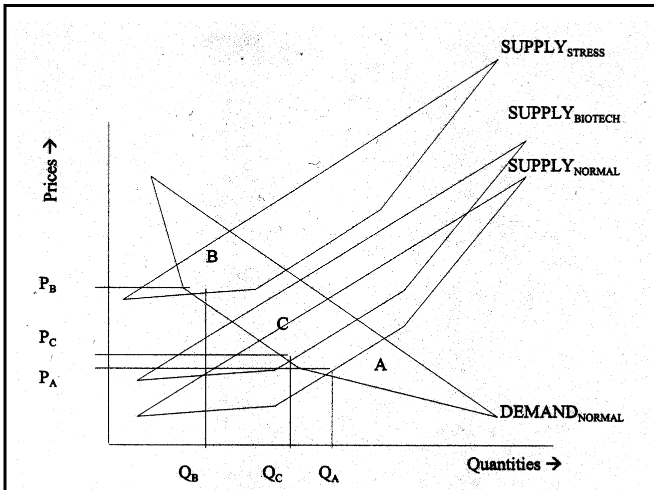

Figure 1. Biotechnology innovation to counter environmental stresses

Given the impact of environmental stresses, a producer has to either settle for low yields from her fields, or provide additional inputs to plants at additional costs. Even the first option places direct (lower profits) and indirect (alternate procurement costs to honor preseason contracts) economic burdens on the producer.

In case the producer opts for a strategy of maintaining yields, there is an additional cost that must be reflected in the supply curve. In the figure this is shown by a new supply curve called $\text{SUPPLY}_{\text{STRESS}}$. For any quantity point, the supplier would need to charge a higher price; hence this supply curve shifts upwards compared to the “normal” supply curve. In reality the new supply curve would be steeper at higher quantity levels, since there would be input cost non-linearities. But, keeping them parallel does not take anything away from the analysis. Although there is no change to market demand, there is now a new equilibrium at point B – given the new supply curve. At the new equilibrium (point B), there is new set of market clearing price and quantity, where,

$P_B > P_A$ a new higher market price
$Q_B < Q_A$ a new lower market quantity.

In this event, social welfare suffers. Consumers are forced to cutback on their consumption good – which signifies a loss of welfare in any capitalist society. Producers charge a higher price – which run them the risk of product substitution, lower market shares, and possibly lower marginal revenues.

The objective of plant biotechnology is to reverse this eventuality to the maximum extent possible, that is:

$$\textit{Minimize } \frac{\partial W}{\partial S}$$

where, W is social welfare, and S is measurable environmental stress, given by:

$$W = f\,(\textit{Price, Yield})$$

$$S = f\,(\Delta \textit{ temperature}, \Delta \textit{ moisture}, D \textit{ soil salinity})$$

Therefore, biotechnology can minimize $\partial W / \partial S$ by accelerating the natural process of adaptation multiple times with genetic intervention by humans. Hence, plants are able to adapt to stresses within a few generations as opposed to thousands of generations if left to nature.

The effect this has on the market diagram is to push the supply curve down to $\text{SUPPLY}_{\text{BIOTECH}}$. Hence, the new market equilibrium shifts to point C and the market clearing price and quantity move to P_C and quantity Q_C, which lie closer to the normal case. Thus plant biotech represents a net welfare gain for any society that is suffering welfare losses resulting from environmental stresses, and is given by the area within the quadrangle P_BBCP_C.

BIOTECHNOLOGY IN AGRICULTURE AND FOOD

There have been limitless possibilities of application of biotechnology in the agricultural sector. Genetically modified (GM) plants and crops in the agriculture sector offer the potential to increase yields, lower costs and reduce the use of agrochemicals. The financial benefits of using biotechnology have been huge. There are also several environmental benefits. For example, worldwide sales of chemicals used in crop protection totaled about $ 30 billion in 1997. It is predicted that this may decrease by 50% within 13 years because of disease resistance varieties of grains and oilseeds (Lyseng, 1997).

A variety of agricultural products produced by GMOs (refer Table 2) has already been available in markets and more are pending federal approval. There were about 50 million hectares of GM crops grown worldwide in the year 2001 (James, 2001). The early emphasis of ag-biotech was on the reduction of farming costs and the increase of plant yields by developing insect / disease resistance, and herbicide tolerance crops. Insect resistant and herbicide tolerant crops constitute the majority of currently adopted bioengineered crops. In addition to reducing costs, this approach has been beneficial in reducing the amount of pesticide, insecticide, fungicide applications – thus minimizing human health risks and groundwater contamination.

Environmental benefits of reduced chemical pesticides may appeal to environmentalists. For example, eight GM crops improved crops yields by 4 billion lbs and resulted in savings of 1.2 billion as a result of lower production costs and reduction in pesticide use by 46 million lbs in the US (NCFAP, 2002).

These 8 crops are: insect-resistant corn and cotton; herbicide tolerant canola, corn, cotton and soybean; virus resistant papaya and squash. Of these eight crops, greatest yield increases have occurred for insect–resistant corn (3.5 billion lbs) and insect-resistant cotton (185 million lbs). Most cost savings have occurred in herbicide-tolerant soybeans ($133 million) followed by herbicide -tolerant cotton (58 million). The use of herbicide tolerant soybean resulted in the reduction of 28.7 million lbs of herbicide (NCFAP, 2002). It is predicted that the greatest increase in yield among GM crops is likely to occur with fungus-resistant barley (1.44 billion lbs).

Similarly, future yields have been projected to increase by 1.42 billion lbs with herbicide tolerant wheat, 1.4 billion lbs with herbicide tolerant sugarcane and 1 billion lbs with potatoes resistant to viruses and insects. As well, fungus-resistant potatoes could eliminate the use of 28 million lbs of soil fumigant. Likewise, it is estimated that rootworm resistant corn could reduce the application of 14 million lbs of pesticides. Overall, the adoption of biotech crops is expected to increase yields by 5.5 billion lbs, minimize the costs by $187 million and preclude pesticide use by more than 91 million lbs annually (NCFAP, 2002). In the food industry, biotechnology offers a multitude of new and challenging opportunities such as testing for pathogens using monoclonal antibodies, food processing enzymes, health promoting ingredients (also called *nutriceuticals*), and designer feedstocks with unique functional properties.

It has been argued that although pharmaceutical applications of biotechnology dominate the developments at present – as evidenced by the rising number of biotech drugs approved each year (Fig. 2) – they will soon be exceeded by the food and agricultural applications (Finely and Scheinbach, 1996). In the food sector, the obvious benefit of biotechnology has been the cost-effective production of valuable enzymes used in the food processing industry. For example, sales of chymosin were about 0.5 billion dollars (Finely and Scheinbach, 1996). Designer fats are another rapidly growing business. Lipases have shown the possibility producing low calorie fats such as caprenin or salatrim at lower costs.

Besides providing food products, plants are also rich sources of insecticides and anti-microbials. Importantly, most of these pesticides and microbials are biodegradable and many are not synthesized by plants until their production is triggered by the pest invading the plant. Scientists have been working to enhance the resistances of a wide range of plants of agronomic value against viruses, bacteria, insects, etc. Virus resistance has been successfully applied to crooked-neck squash.

The objective of this branch of plant-biotech is to replace the use of toxic chemical pesticides with biological compounds that are synthesized by plants thereby reducing environmental degradation. Herbicide tolerant crops such as soy, corn, sugar beet, and rapeseed have already been developed. Hence, herbicides like glycophosphate can be applied to kill weeds without affecting these crops. Since glycophosphate is degraded by soil organism, the end result is a no residue pesticide (Finely and Scheinbach, 1996). Corn has been genetically modified to produce a toxin that kills the corn borer but not other insects or animals, and excluded the need to use insecticide.

It is important to develop stringent standards for this industry to ensure that toxin levels synthesized by plants do not exceed the levels harmful to living organisms in par with the conventional pesticides industry. Although the debate on toxicological risks of synthetic chemicals versus the pesticides produced by transgenic plants is unavoidable, the transgenic pesticide has an obvious advantage because it is produced only when needed and affect only a target pest population. While producers benefit by having lower labor and pesticides costs, consumers benefit through the lower cost of the product and better health and environmental safety. Consumers, however, may not initially realize the cost benefit since companies add monopoly premia to the products to recover investments in R&D (Finely and Scheinbach, 1996).

Table 2. Applications of ag / food biotechnology

Examples of current ag and food biotech products	Expected future products from biotechnology
Milk from cattle receiving BST	Rapid growing salmon
FlavrSavr tomatoes	Improved tomatoes
Improved cherry tomatoes	High solids tomatoes, potatoes
Carrots	High stearic rapeseed oils - shortening and frying
Sweet mini-red peppers	MCTs from rapeseed
Chymosin cheese	Low saturated fats from rapeseed
Aspire- natural fungicide	Pest resistant rice
Nisin - cheese protection	
Pest resistant corn, wheat, cotton, potato	

Plant-biotech is making major inroads in enhancing agronomic performance traits of plants. For example, genes associated with resistance to drought, cold, salinity and other environmental stresses, have been identified. Yields will be improved dramatically by transferring such genes to other plants (transgenic plants) that lack the natural ability to withstand drought, cold, salinity, etc.

To realize the scope of biotechnology in the agriculture sector, investments in research and development are very crucial. Since biotechnological products are well suited to international trade and commerce, companies willing to invest in biotechnology always look to the international market to recover their investments. Therefore, the decisions on investments in biotechnology products are guided by considerations such as international trade barriers, regulatory constraints, etc. Existence of market imperfections can undermine the incentives for investment in ag-biotech (Klein et al., 1998).

There are four requirements for achieving the best return on investment in biotechnology research. First, the product should demonstrate profitability and easy access to farmers. The product must primarily be appealing to the consumer (e.g., *FlavrSavr* tomato has distinct commercial advantage since it improves shelf life and flavor), and environmental health is only a positive externality of this process. Second, there should not be long delays in governmental approval and testing requirements. Third, biotechnology products must be protected by intellectual property rights. In the face of a weak intellectual property rights regime, companies may find their investment risky. Fourth, biotechnology products must have a secure passage to international markets.

For biotech products to succeed in the market, end use benefits should be communicated to consumer. *FlavrSavr* tomato has been well accepted by consumers in California. In contrary, milk produced by using bST initially did not do well in the markets due to little perceived consumer benefits. Furthermore, scare tactics used by advocacy groups succeeded in dissuading the public in using the milk produced by cows receiving bST. To have a level playing field for biotech products, efforts must be made to communicate the benefits and safety to consumers.

Higher yields, higher quality, and lower cost of production notwithstanding, the promises of ag-biotech have been tempered by risks that come with genetic manipulation. There are serious concerns regarding the ultimate impact of biotechnology in food and agriculture. One major problem with transgenic food products is the inability to assess the long-term effects of these products in the short-term. Little is known about the long-term toxic buildup and environmental effects of transgenic products.

The possibility of gene contamination due to genetic manipulation between and among species has worried consumers and many critics. It is a very complex task to keep genetically modified grains from natural seeds. It is also difficult to control mixing of different plant genotypes in large-scale agriculture. Although the possibility of cross- pollination generally decreases with distance, it is virtually impossible to estimate the distance that ensures zero pollination. Measuring and monitoring has been a major focus in recent years in European and North American agricultural system (Gates, 1996). There is international consensus for carrying out a comprehensive safety assessment before GM crops are released into the environment and grown commercially in agriculture (Dale and Kinderlerer, 1995). It has been argued that although gene transfer from transgenic groups to wild species is possible, this will not be considered sufficiently harmful on a local scale to prevent the release of genetically engineered crops in advanced Western agricultural systems (Rogers and Parkes, 1995).

Critics often argue that the benefits of biotechnology have been overemphasized while downplaying the associated risks. GM crops can aggravate or alleviate the impact of agriculture on the environment. They can aggravate the problem if they promote monoculture. On the other hand, they can alleviate the impact of agriculture on the environment by targeted genetic control of pest and disease (Dale, 2002). However, claims that GM crops such as herbicide resistant crops offer environmental benefits are rarely supported by a thorough cost-benefit analysis that takes into account all potential environmental impacts (Gates, 1996). Historically, an adversarial relationship has existed between the proponents of plant biotechnology who strive for rapid practical application and non-governmental organizations, consumers and pressure groups that advocate the precautionary principle and fight for more equitable use of new technology and more stringent safety measures (Lindsay, 1995).

There are unlimited opportunities of biotechnology in agricultural and food sector. However, in addition to the technical hurdles, some barriers must be overcome: market imperfections, the issue of who bears the cost for development, and who has property rights for the products, public perception of costs and benefits, and the regulatory environment. The success of biotechnology in the agriculture and food sector will largely be determined by consumer confidence in the safety of biotech products and the capability of producers in dealing with the questions of containment and segregation of transgenic produce with scientific objectivity.

BIOTECHNOLOGY IN FORESTRY

With biotech developments occurring at an unprecedented scale, forestry today stands on the threshold of a promising change. Biotechnology applications in the forestry sector can be categorized into the broad areas of - vegetative reproduction, genetic markers, and genetically modified organisms (GMOs), or transgenic trees (Sedjo, 2001).

Currently, biotechnology research in forestry focuses on identifying genetically superior trees, propagating trees through tissue culture, improving trees through genetic engineering, protecting forests with biological pest-control methods, and assessing environmental impacts of biotechnology-derived products. Genetic engineering and advanced tissue cultures for cloned seedlings offer many benefits at a time when we depend on natural forests for wood products and other services and their destruction is occurring at a rapid rate. Basic techniques in tissue culture, genetic transformation, and molecular genetics have been applied to forest trees with varying degrees of success. Biotechnological innovations such as herbicide resistance, fiber modifications, lignin reduction and extraction, sterility have yielded unique benefits to the forestry sector. There are both economic benefits such as lower costs and increased availability of wood and wood products as well as environmental benefits such as rehabilitation of habitats, reduced pressure on natural forests from increased productivity, and restoration of habitats in previously unsuitable areas. The application of biotechnology to forestry holds the potential for trees that grow faster, require the use of fewer chemicals in pulp and paper production and thus has less of an impact on the environment.

Today, a majority of biotechnology applications in forestry relate to tissue culture and molecular marker applications. Nonetheless, there is enormous potential for the use of transgenic trees. Specific genes responsible for certain traits can be identified and introduced to the plant genome. For example, the lignin content, type, and form in wood can be altered to assist in papermaking by identifying and modifying lignin genes.

The primary economic advantage of introducing biotechnology in forestry is improved productivity. This can result either from yield increases or cost reduction or both. Wood products derived from plantation forestry have a competitive edge in the market over those derived from natural old-growth forests because of associated cost-reducing technology with plantation forestry. Economic advantages also result from improved traits such as straight trunks with little branching, disease resistance, low lignin content in wood, etc. Desired characteristics vary according to the enduse of the wood. For example, one set of fiber characteristics is desired for milling and carpentry whereas another set of fiber characteristics is desired for pulp making. Some characteristics are valued for their role in the production processes (Sedjo, 2001). In pulp making, easy breakdown of wood fiber and lignin removal is desirable. Wood value can be increased by customizing the raw materials for specific needs.

A multitude of environmental benefits can be realized from biotechnology (Table 3). The obvious one is the reduction of pressure on primary forests, which are prized for biodiversity and wildlife habitat, by substituting with genetically customized plantation wood. It has been argued by forest scientists that that biotechnology can enable fast growing plantation forests that would help the industry meet demands that have grown by as much as 300 percent in the last 25 years without having to harvest native forests (Roach, 1999).

Biotechnology also plays an important role in ecosystem restoration. For example, wild tree species such as the American Chestnut that has been eliminated by disease can be restored by introducing disease resistant transgenic varieties. Modified tree species with improved drought or cold resistance is useful in providing environmental services in areas where trees are difficult to grow. Carbon sequestration, which is an innovative strategy to help mitigate the anthropogenic greenhouse effect, can be enhanced by afforestation of degraded lands using transgenic trees.

Table 3. Economic and environmental benefits of using biotechnology in forestry

Economic benefits	Environmental benefits
Increased productivity Production cost reduction Improved specific values such as tree form (straight trunks with minimal branching) , diseases resistance, low lignin content	Reduced pressure to log primary forests due substitution of plantation wood for wood from natural forests Establishment to protection forests in degraded lands Establishment of carbon sequestrating forests on sites previously not suitable for forestry

However, the forestry sector is not immune to criticisms surrounding any transgenic technology. Biotechnology innovations raise concerns about bio-safety and effect of transgenic plants on the resistance of pathogens and genetic exchange between domestic and wild populations. For trees, which are not strictly food sources, the question of food safety is not usually raised. However, with increasing use of cellulosic material as filler in food products, the use of transgenic trees may start raising food safety issues. Another concern is the possible gene contamination of wild tree species from transgenic trees. If plantation trees are exotic, then the issue of migration to the natural environment would not arise. In cases where gene flow to natural environment is a concern, planting sterile trees or varieties with delayed flowering would minimize the likelihood of gene leakage (Sedjo, 2001). If the genes in question are not survival genes, the presence of modified genes, (e.g., genes that affect fiber characteristics, or tree form) in the natural environment will not pose a serious problem because they are unlikely to provide a competitive advantage in survival and therefore do not exert adverse consequences.

In cases where survival genes are involved, the consequences can be serious. The release of the *bacillus thuringeinsis (bt)* gene, which imparts pesticide resistance to plants, into the natural environment would cause a problem if it altered the comparative competitive position of wild vegetation in dealing with pests. Another concern is that pests may adapt to such genetic pest controls through natural selection thereby undermining the long-term effectiveness of the *bt* gene. Since trees generally have long growth periods, it would allow insect populations many generations to develop resistance mechanisms. One strategy suggested to extend the life of transgenic pest control would be to establish "refugia" (places planted with trees without Bt gene) that undermine the ability of pests to develop resistance through natural selection (Sedjo, 2001).

Overall, the magnitude of the problem of transfer of survival genes into the environment is determined by the probability of transfer of a survival gene, the scale of transfer, and change in the comparative competitive position in the natural habitat. Considering that trees have long lives, largely undomesticated status, poorly understood biology and lifecycles, and the complexity and fragility of forest ecosystems, planting GM trees may create grave risks (WRM, 2002). One way to reduce the conflict between adversarial groups is to require environmental impact assessment, with full-disclosure of all potential benefits of bioengineered trees and risks including information gap and uncertainties that may have environmental consequences (Lindsay, 1995).

To sum up, biotechnology can address the challenge of meeting demand for wood and wood products with less environmental intrusion. Research done over the years have shown that it is practically possible to obtain trees with new growth characteristics, altered processing capabilities, improved resistance to external threats and commonly valuable traits. Given the far-reaching implications of impact biotechnology in forestry, societal, ecological and economical benefits must be ensured. The application of biotechnology in forest sector should be evaluated for safety and appropriateness. This can be done by bringing together issues related to science and research, industry and commercialization, ecology and environment, and policies and taking a holistic approach to tackle the problem (IFB, 2002).

ENVIRONMENTAL BIOTECHNOLOGY

The area of environmental biotechnology directly addresses specific issues relating to the mitigation of pollution, and extends to conservation including areas like supplying alternate environment-friendly bio-resources and biosensors for assessing environmental health. Specifically, environmental biotechnology makes use of micro-organisms for treatment of toxic and hazardous wastes converting them into harmless substances.

It may be noted that the biotechnology also renders positive environmental externalities from a variety of other functional areas including food, forest and ag-biotech, by either reducing environmental damage or improving the productivity of an environmental resource. Biotechnology also supplies environmental benefits through sustainable industrial processes or improved industrial ecology. The direct application areas of environmental biotechnology are:

1. GMOs to assimilate pollution – e.g., oil eating bacteria, PCB reducing bacteria, etc.
2. Environmental monitoring – assess air / water qualities
3. MTBE assimilation – microbes that neutralize MTBE (gasoline additive)
4. Material and energy inputs – biomass used as energy inputs, biodiesel
5. Biocatalysts / bioenzymes – environment-friendly industrial processors
6. "Green" plastics – biodegradable materials and biopolymers

Environmental biotechnology also benefits several industries by providing alternate resources and processes, such that these industries can continue to grow while complying with the regulatory regimes.

INDUSTRIAL BIOTECHNOLOGY

To establish sustained growth in the chemical industry, interests in the pursuit of biotechnology has been growing with a view to develop materials with higher information content and improved economics. Many chemical companies such as Dupont, Dow, BASF and Monsanto are involved in creating high-value materials through biotechnology. In the early years of biotechnology development, most of the R&D funding ($10 billion) was devoted to pharmaceutical and agricultural products, like antibiotics, amino acids and enzymes, via fermentation. In the chemical industry, biotechnology has made its presence felt in three ways:

1. Created new molecular targets for the industry to manufacture;
2. Provided new catalysts for carrying out chemical unit processes ; and
3. Provided new and cheap raw materials, sometimes very complex ones which have potential to create new areas of chemistry (Bryant, 1994).

In recent years, industrial bulk enzymes produced by using recombinant microbes have become important input materials for the detergent, paper processing, diary, textile and feed industries. In 1990, the worldwide bulk enzyme production was valued at US $720 million (Nielsen, 1994). Many of these industries require a wide range of chemicals, therefore, it can be expected that the use of enzymes will continue to grow. Recently, superior strains of microorganisms have been isolated that provide higher productivity of a desired enzyme, greater thermal stability, or a speedier reaction time. Researchers have developed a fermentation process that avoids multi-step chemical synthesis and produces semi-synthetic L-amino acids. This process is more cost effective since it uses glucose, a relatively low-cost raw material (TI, 2003).

Research and development in the improvement of enzyme properties and function will lead to further displacement of chemicals in these industries. For some amino acids, the method of production has shifted from chemical processes to bioprocesses. For example, acrylamide has been produced commercially by using a third-generation biocatalyst (amino acid) since 1985 by Mitsubishi-Rayon (Yamada and Kobayashi, 1996).With the use of biotechnology it is possible to achieve large-scale commercial production of polymers from lactic acid, which in turn can be obtained from fermentation of renewable sources such as sugars. This shift from chemical to biotechnological processes can minimize potential environmental concerns associated with the disposal of chemical processing wastes while increasing product yield.

In the chemical and materials industry sector, a new opportunity has been opened with the possibility of integration of chemical and materials sciences with biotechnology. Chemists have produced a number of synthetic polymers with wide-ranging functionalities. Similarly, biologists have succeeded in engineering the production of proteins, polysaccharide, nucleic acid, polyhydroxy alkanoates, etc. Given the similarities between biopolymers (e.g., protein) and synthetic polymers, a better understanding of the structure and function of synthetic polymers and biopolymers will make it possible to design biomimetics with characteristics derived from the structures of both types of polymers.

In essence, biotech products can have huge impact on materials technology in synthesizing high-information-content materials (Miller and Nagarajan, 2000). Bioprocess is suited to the economic production of such chemicals products. A single, large batch fermentor can be employed to manufacture a multitude of enzymes and antibiotics. Besides lower capital costs, the use of renewable raw materials is another advantage for bioprocessing.

The next phase of successful commercialization of large-scale monomers may involve the manipulation of multiple pathways and genes in a heterologous host, as is the case in the production of 1,3-propanediol (Laffend, 1997). Genomics and array technology can be applied for metabolic engineering thereby reducing the cycle time in the production of robust biocatalysts (Bailey, 1999). A major hurdle that remains in the successful commercialization of bioprocess is how to achieve efficient downstream processing. Since bioprocess is water-based, problems such as high hydraulic loads and biofouling are common. Material recovery will be expensive unless a new separation technology is developed. However, chemical engineering is responding with the development of necessary tools that have proven valuable in the development of biochemical engineering (Miller and Nagarajan, 2000). Emerging technologies such as *in situ* product-removal and molecular-imprinted polymers will provide novel solutions (Lye and Woodley, 1999). The integration of biotechnology with materials sciences is likely to generate a societal impact similar to that of information technology – since it promises to dramatically expand the scope of material use, both in terms of the size and nature of applications

BIOPHARMACEUTICALS

Advances in biotechnology now address the entire gamut of issues relating to the human body, including the requirements of a healthy body, causalities of divergence, measuring the signals of dysfunction and innovative remedial strategies. Some of the sub-areas of this development are (BIO, 2003):

Diagnostics – early, accurate and sensitive detection of physiological change
Therapeutics – biological substances from nature's molecular production system
Nutriceuticals – naturally occurring compounds that have remedial potentials
Biopolymers – biological molecules as surgical aids, prosthetics and for drug-delivery
Protein replacement – like insulin (missing in diabetics), Factor VIII (hemophiliacs)
Genetic therapy – for treating hereditary disorders
Cell transplants – for regenerating organ tissues, cartilages, etc.
Immunology – stimulating or suppressing the immune system
Vaccines – production of antigen
Genomics and proteomics – molecular basis for disease, aging
Xenotransplantation – organ transplants from other species.

This is the fastest growing functional area in the field of biotechnology, and the prospect of biopharma drugs is evidenced from the steeply sloped graph (Figure 2) of approvals since 1995.

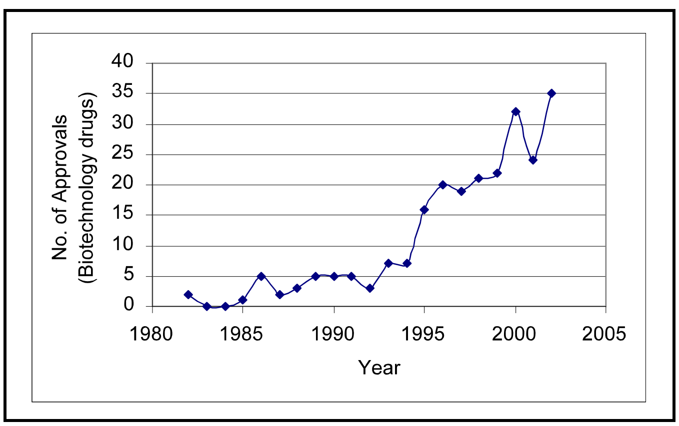

Figure 2. Growth of biotechnology drugs

While several new biopharmaceuticals have been developed recently (refer Table 4), there is an exciting new sub-field known as Plant-made-Pharmaceuticals (PMPs). Using plants as factories for growing therapeutic proteins is a low-cost innovation that avoids many of the complications of mammalian cell-culture methods. PMPs are made by tapping the extraordinary ability of plants to manufacture complex proteins, given the appropriate genetic information (Monsanto Protein Technologies, 2003).

Production economics could also favor PMPs over other biopharma options. While classical chemical therapeutics cost about $5 per gram, it could cost between $100 to $500 per gram to make a protein therapeutic using bacterial cell culture, and the price tag could be upwards of $1,000 per gram if mammalian cell culture is used. Using PMPs could drive the cost down by at least 50% compared to bacterial cell cultures. Moreover, there are additional costs resulting from entire batches being rejected for any hint of contamination or minor deviations from strict regulatory standards for storage, etc. These costs are almost eliminated because of the inherent stability of the PMP process.

Table 4. Use of biotechnology in medical applications

Biopharmaceuticals in current development, testing, federal approval	Areas of future biopharmaceutical developments
Human insulin Human growth hormone Interferon TPA Clotting factor Serum Albumin Tumor Necrosis factor Nerve growth factor Relaxin Antigen only (microbe-free) vaccines for meningitis, hepatitis-B	Bio-diagnostics for a variety of applications DNA vaccines (HIV, malaria, flu, diabetes, Alzheimer's, hepatitis) Rheumatoid arthritis Gene treatment for cancer Delay aging, increase longevity

PROGNOSIS: PERILS, PERPLEXITIES AND ECONOMIC PROMISE

The biggest worry of transgenic production is containment and segregation. Although the magnitude of environmental costs, from accidental breaches of containment, is not clearly defined, it is easy to speculate on the irreversible damages that may be caused to ecosystems directly from a GMO that possesses foreign genes (that it would never have acquired in the natural process) and also the indirect impacts of its interactions with other species. Hence, whatever the product, any breach of containment guidelines will result in a clear, present and future peril.

Adoption of any new technology at the consumer level is a slow process that is encouraged by demonstrations of benefits as well as obvious attention to safety issues by producers and regulatory authorities. The current state of biotechnology is that it neither enjoys a clear exposition of benefits by credible sources, nor is it favored by an unambiguous addressal of risks by producers and regulators. This, along with sensationalization of biotech accidents (e.g., StarLinx corn) – without adequate coverage of follow-up activities and research – has led to a buildup of perplexity in the public psyche. Important safety and containment initiatives have often gone unreported in the media. For example, the problem of gene leakage into the natural environment can be prevented, by the strategy of introducing only sterile species.

At this stage, it is important to increase the level of public awareness for wider adoption of this technology. This is a multi-dimensional task that needs to be addressed by businesses, industry groups, professionals and regulators alike.

The biggest adoption of biotechnology, so far, around the world has been in the crop sector where GMOs are attractive to producers for their enhanced agronomic properties. For example, GM acreages have gone from less than 5 million acres in 1996 to about 150 million in 2002 – a 30 fold growth in 6 years. There are at least 2 dozen other grain and vegetable crops (e.g., potato, rice, sugar beet, squash) that will be launched in the near future with attributes as diverse as insect resistance, better color, longer shelf-life and delayed ripening (Nap, 2003). There are several economic benefits of such adoptions, including, avoiding pre and post harvest losses to pests, higher value added due to better consumer features and avoided costs of environmental degradation from agrochemicals.

In addition, the rDNA technology is easily extended to biosensors and biomarkers which are bound to prove invaluable in the future. Biotechnology is a powerful tool that will not yield its true potential to society if it is limited to the handful of industries that have currently adopted or experimented with it. Even as viewed from today's state of the art, it holds great promise for new lines of diagnosis and treatment for both genetic disorders and pathogenic ailments. Combined with parallel developments in nanotechnology, it can provide substantial social value from the standpoint of human health alone.

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