

Products from plant biotechnology

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Crop plants have been continually modified genetically and improved for centuries, beginning by selecting seed from superior plants and reproducing these through selection and breeding. Traditional breeding methods have significantly increased productivity, with corn and wheat yields approximately doubling over the past 40–50 years. More recently, the ability to introduce DNA directly into crop plants has enabled very specific and selective plant improvement through techniques commonly referred to as plant biotechnology, genetic engineering, or recombinant DNA methodology. Numerous traits are being evaluated for their potential to:

- 1) protect plants against insect damage, and fungal, viral, or bacterial diseases
- 2) provide selectivity to preferred herbicides
- 3) directly enhance crop yields
- 4) increase nutritional value
- 5) reduce naturally occurring toxicants or allergens
- 6) modify the ripening process and provide fruits or vegetables with superior flavor
- 7) use plants as factories to make biodegradable polymers, pharmaceutical products, and many other products.

Plant biotechnology is critically needed in view of the rapidly growing world population, the loss of topsoil by erosion, and the loss of tropical forest, grasslands, and other sources of biodiversity, all major challenges of global importance. For example, combining the projected doubling of the global population with the simultaneous increased demand for higher protein-containing foods results in tripling the amount of food that will be needed in the next 40–50 years. Even today, an estimated 800 million people, including 200 million children, are chronically undernourished in the developing world, and millions suffer from diseases associated

with micronutrient deficiencies. To put this challenge into perspective, the world will have to produce twice as much food in the next 40–50 years as has been produced in the history of our civilization.

Plant biotechnology provides an important tool to help meet many of these challenges, a tool that must be effectively integrated with the best current agricultural practices to be successful. Effective global cooperation and utilization of the most productive and environmentally appropriate technologies is critical to meet these challenges. This paper will provide a brief overview of the current status of plant biotechnology and information on some of the products that have been developed and that are under development.

Current status of plant biotechnology

Today, some 16 years since the development of the first genetically modified plant, methods have been developed and implemented such that essentially all economically important plants have been genetically modified. By the end of 1997, more than 25 000 field tests had been done in a total of at least 45 countries with at least 60 different genetically modified crops (1). Literally hundreds of different genes have been introduced into plants by thousands of laboratories around the world.

Following extensive field testing, at least 48 different products have been approved for marketing by the appropriate regulatory authorities in at least one country. Approximately 7 million acres of genetically modified plant products were grown commercially in 1996, approximately 31 million acres were grown in 1997, and over 65 million acres are projected in 1998. The details of many of these products will be briefly discussed.

Important traits

It is beyond the scope of this paper to discuss all the traits that have been tested and the products that have been approved; therefore, classes of the most advanced traits and important products will be briefly discussed. According to the World Wide Web site (<http://www.aphis.usda.gov/bbeg/bp/>) provided by the USA Animal and Plant Health Inspection Service (APHIS), the most frequently field-tested traits are insect protection, virus protection, fungal resistance, herbicide tolerance, and food-quality enhancements. In addition to these traits, several more recent and important areas of research will be briefly summarized, including the use of genetically modified plants as factories for the production of biopolymers, pharmaceuticals, and vaccines.

Insect protection

Several different approaches have been evaluated to control various insect pests that cause tremendous damage to crops (2). These insect pests have typically been controlled by the use of chemical insecticides. Insecticides and associated management practices cost approximately \$10 billion annually worldwide. Yet, 20–30% of the total crop product is still lost due to insect pests. Insect-protected, genetically modified plants were among the first genetically modified plants to be field tested and marketed because of the value associated with effective insect control and the availability of microbial genes with insecticidal activity.

Genes derived from the bacterium *Bacillus thuringiensis* (*B.t.*) have been used to produce commercial cotton, potato, and corn products protected against the major insect pests of these crops. *B.t.*-based microbial products have been used commercially since 1961, establishing a long history of safe use. The insecticidal proteins produced by *B.t.* are extremely specific and selective, due to a receptor-mediated binding in the insect gut. However, the microbially produced products account for less than 1% of all pesticides used in the USA due to disadvantages such as expensive production and application, need for repeated applications, inactivation by sunlight, and being washed off by rain. These disadvantages were overcome by introducing genes encoding these proteins directly into the desired crop. These bacterial genes were modified to increase the level of expression of the insecticidal protein in the plant to levels sufficient to provide season-long protection against the targeted insect pests. Use of these products reduces chemical insecticide use, enhances environmental safety, reduces energy and

labor costs, and improves the quality and quantity of the plant product. The effectiveness of this approach is demonstrated by successful launches of insect-protected potato, cotton, and corn products.

Approximately 1.8 million acres of genetically modified insect-protected cotton varieties were grown in the USA in 1996, accounting for approximately 13% of the US cotton crop. Approximately 2.2 million acres were planted in 1997, with 2.6 million acres projected for 1998 in the USA. In addition, insect-protected cotton varieties are being planted in Australia, Mexico, South Africa, and Argentina. These plants provide protection against the three major insect pests in cotton: tobacco budworm (*Heliothis virescens*), pink bollworm (*Pectinophora gossypiella*), and cotton bollworm (*Helicoverpa zea*). US cotton growers planting these varieties reduced their chemical insecticide use by 250 000 gallons in 1996 alone. Increased effectiveness in control of these insect pests resulted in an average increase of 7% in cotton production, or \$33/acre income advantage in 1996, while also resulting in increased numbers of beneficial insects due to the specificity of the pesticidal protein.

Approximately 10 000 acres of genetically modified *B.t.* potato plants protected against the Colorado potato beetle, the most damaging potato insect pest, were planted commercially in 1996. Approximately 25 000 acres were grown in 1997, with 50 000 acres projected in 1998. Growers planting the insect-protected potato plants used approximately 35% less insecticide to control the Colorado potato beetle than growers planting non-insect-protected potato varieties.

Approximately 400 000 acres of genetically modified *B.t.* corn plants protected against the corn borer were planted commercially in 1996. Additional insect-protected corn products entered the market in 1997, which significantly increased the acreage to approximately 8 million acres or approximately 10% of the US corn crop. In 1998, over 20 million acres of insect-protected corn is projected, accounting for approximately 30% of the US corn crop.

Research continues to develop insect protection in many other crops, e.g., tomato, rice, peanuts, soybeans, and chickpeas, through expression of *B.t.* proteins. To date, hundreds of different genes have been isolated and characterized from a broad spectrum of *Bacillus* species. With this diversity of genes, many additional insect pests will be controlled and crops protected. Of course, one of the primary aims of those involved in the development of these products is to ensure the long-term durability and effectiveness of these products. To this end, numerous strategies have been developed

and are being implemented and refined to ensure that these products maintain their long-term effectiveness.

Virus protection

Virus-resistant, genetically modified plants have been produced by using genes derived directly from the virus, the so-called pathogen-derived resistance (3). The first genetically modified plants, tobacco plants with increased resistance to tobacco mosaic virus (TMV), resulted from the expression of the TMV coat protein in tobacco plants. This coat protein-mediated resistance has been used extensively to confer viral resistance on numerous crops, including tobacco, tomato, squash, melon, rice, papaya, potato, and sugar beet. In 1987, TMV-resistant tomato plants were the first genetically modified tomato plants to be field tested.

Squash varieties resistant to zucchini yellow mosaic virus and watermelon mosaic virus were approved in the USA in 1995 and marketed. These two viruses routinely reduce crop yields by 20–80% depending on production season and growing region. More recently, squash plants resistant to these two viruses and a third destructive virus were developed. Marketing of these products enables more consistent production of squash varieties and significantly reduces the use of chemical insecticides that are typically required to control virus spread by insects.

Several other viral-derived genes have been identified to provide effective control of viruses. For example, resistance to the most economically important virus disease in potato, potato leafroll virus, was achieved by introducing a gene involved in viral replication. This virus typically causes decreases in potato tuber quality and reductions in potato production worldwide. In the future, combinations of virus resistance with resistance to key insect pests will be critical, since insects often serve as vectors to transmit viruses. Combining these traits within plants will lead to even more impressive reductions in chemical insecticides and the accompanying energy and resource savings associated with the production, distribution, and application of synthetic chemical products.

Fungal/bacterial disease resistance

The identification of antifungal genes and the production of genetically modified plants that effectively control fungal disease lags significantly behind the production of insect- and virus-resistant plants. Recent advances, however, indicate that this will be only a temporary situation; genetically

modified plant products that are effective in controlling important plant diseases are being produced and evaluated (3).

Selectivity to herbicides

Weeds compete with crops and reduce yield, decrease harvest efficiency, decrease seed quality, and serve as a reservoir for crop pests, and they can devastate a crop if not controlled. Agricultural practices used prior to World War II were labor intensive and contributed to soil erosion. These processes have been replaced by the use of chemical herbicides that are the most effective, reliable, and economic method of controlling weeds on a large scale. Today, herbicides are used on 95% of the acreage of the major agronomic crops in developed countries.

Conventionally, herbicides have been selected according to the weeds to be controlled and the natural resistance of the crop to the herbicide. The use of this system has been tremendously successful in providing the grower with effective weed control. Biotechnology provides an opportunity to modify crops to tolerate selected herbicides with preferred environmental properties, such as glyphosate. These herbicide-tolerant crops allow the farmer to apply herbicide to planted fields, killing weeds but leaving the planted crop unaffected. This ability provides increased flexibility and cost savings to growers. In addition, farmers can move from using pre-emergent, soil-incorporated herbicides to post-emergent herbicides that are applied on an as-needed basis. This strategy can reduce the number and total amount of herbicides used and enable the application of herbicides that bind tightly to the soil and are less likely to enter the ground water, thereby providing significant environmental benefits.

Soybeans, canola, cotton, and corn tolerant of glyphosate are examples of genetically modified, herbicide-tolerant crops that are entering the marketplace (4). For example, glyphosate-tolerant soybeans were planted on over 1 million (approximately 1.5%) of the US soybean acres in 1996 by over 10 000 growers. Because of exceptional weed control and crop safety, these soybean varieties yielded an average 5% more per acre than soybean fields planted with the same varieties but treated with conventional herbicide programs. Approximately 75% of the growers used only one herbicide application, providing a significant reduction in the number of herbicides used compared to soybeans treated with conventional herbicide programs. In 1997, approximately 9 million acres (9%) of the US soybean acres were planted with glyphosate-tolerant soybeans. Over 25 million acres or 35%

of all US soybean acres will be planted in glyphosate-tolerant soybeans in 1998.

Food-quality enhancements

Although many of the initial genetically modified plant products have improved agronomic traits, the first plant biotechnology product marketed in the USA, the Flavr Savr™ tomato, is a product with food-quality enhancements. Many additional products with improved quality or nutritional properties are under development.

Texture, taste, and aroma are important aspects of food products intended for direct consumer purchase. Five tomato products have been approved in the USA which result in improved ripening and/or softening processes, allowing the fruit to ripen longer on the vine or have an increased shelf life. These enhancements have been achieved either by inhibiting the breakdown of cell-wall components or by directly altering the synthesis of ethylene, the phytohormone that triggers the fruit-ripening process.

Carbohydrates

Modifications of the carbohydrate content and specific carbohydrate composition in foods represents a significant opportunity to improve food quality and nutrition, since these are the most important sources of energy in the diet. Among food crops, corn, rice, wheat, potato, and cassava provide major contributions to the intake of dietary carbohydrate, typically in the form of starch. The total amount of starch has been increased in potatoes by introducing a gene encoding the nonregulated bacterial enzyme, ADP-glucose pyrophosphorylase, which is the key regulatory enzyme controlling starch biosynthesis in plants (5). Strategies to ensure the uniformity of the increased starch content throughout the potato are being assessed, as this would lead to enhanced performance characteristics in potato chips and French fry products. The increase in starch content has been achieved at the expense of water content, resulting in both greater yield of processed potato products as well as reduced absorption of oil when frying. Consequently, potato chips and French fry products from these potatoes will have reduced fat and caloric content. In addition, tomatoes containing increased starch provide energy conservation and other economic benefits by reducing the amount of energy-intensive processing required for the production of tomato sauce and tomato paste-based products.

In addition to modifying the total starch content, modifications in the composition of starch also have

been achieved. For example, amylose-free, amylopectin-enriched potatoes have been produced by inhibiting the production of granule-bound starch synthase to produce starch preferred for specific industrial applications. In addition, by redirecting the flow of carbon from starch biosynthesis, increases in sucrose content and production of new components such as fructans or other sweeteners can also be realized.

Oils

Oils provide the second most important source of food energy for man. Plant biotechnology efforts have focused largely on altering the fatty acid composition of canola, soybeans, and sunflowers, all major sources of dietary oils, to provide either more stable sources of specific oils or oils with enhanced nutritional characteristics (6, 7). The first modified oil product to be marketed is a high laurate canola oil, which serves as an alternative to oils with similar composition, such as tropical oils. A genetically modified canola variety with increased levels of stearic acid and a soybean variety with increased levels of oleic acid already have been extensively tested. The latter product enhances the oxidative stability of the oil and significantly reduces the need for and costs of hydrogenation during oil processing.

Proteins

Foods that provide sufficient quantities of the essential amino acids are critical to meet dietary needs, especially in developing countries where foods low in one or more of these amino acids are often consumed. Approaches to increase the amount of lysine in cereals and methionine in legumes are being assessed. For example, total lysine content of canola, soybean, and corn was increased two- and fivefold, respectively, by expressing non-feedback-inhibited forms of two key enzymes in lysine biosynthesis (8).

Eliminating food components

Plant biotechnology also is being used to reduce or eliminate a number of undesirable food components. For example, the level of one of the major allergenic proteins in rice has been reduced by approximately 80% (9). Efforts to reduce or eliminate other undesirable components of foods, e.g., glucosinolates in canola meal, protease inhibitors in beans, and glycoalkaloids in potatoes, are being evaluated. Components such as caffeine in coffee beans can be eliminated or reduced.

Plants as production factories

Plants provide an unmatched capacity to produce products with maximum efficiency and a minimum of energy – thus, in an extremely cost-effective manner. Efforts are underway to produce protein-based pharmaceutical products, biodegradable polymers, and many other compounds in plants. One of the most exciting applications of plant biotechnology is the ability to produce edible vaccines in plants (10). For example, potatoes containing the binding subunit of the *Escherichia coli* enterotoxin have been produced. This expressed protein functions as an oral immunogen. This technology has exciting implications for technology transfer to developing countries where inexpensive vaccines are urgently needed.

Conclusions

The benefits of genetically modified plant products are starting to be realized as the first products enter the marketplace. Initial benefits are realized primarily by farmers who produce crops with increased yields and quality while requiring less chemical inputs and the use of more environmentally friendly practices, such as decreased tilling. Future generations of genetically modified plant products will include products with enhanced nutritional qualities that will improve the human diet globally. Finally, the possibilities of using plants as clean, efficient factories for the production of medicines, biodegradable plastics, and other

important compounds are just beginning to be explored.

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