Review

The Evolution of Modern Agriculture and Its Future with Biotechnology

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Since the dawn of agriculture, humans have been manipulating crops to enhance their quality and yield. Via conventional breeding, seed producers have developed the modern corn hybrids and wheat commonly grown today. Newer techniques, such as radiation breeding, enhanced the seed producers' ability to develop new traits in crops. Then in the 1980's–1990's, scientists began applying genetic engineering techniques to improve crop quality and yield. In contrast to earlier breeding methods, these techniques raised questions about their safety to consumers and the environment. This paper provides an overview of the kinds of genetically modified crops developed and marketed to date and the value they provide farmers and consumers. The safety assessment process required for these crops is contrasted with the lack of a formal process required for traditionally bred crops. While European consumers have expressed concern about foods and animal feeds containing ingredients from genetically modified crops, Americans have largely been unconcerned or unaware of the presence of genetically modified foods on the market. This difference in attitude is reflected in Europe's decision to label foods containing genetically modified ingredients while no such labeling is required in the U.S. In the future, genetic modification will produce a variety of new products with enhanced nutritional or quality attributes.

Key teaching points:

- Genetic modification of crops is an extension of traditional breeding methods.
- Crops developed via genetic modification undergo an extensive assessment of food and environmental safety prior to introduction on the market.
- Use of herbicide tolerant and pesticide resistant crops results in environmental benefits such as a reduction in pesticide usage and reduced ground water contamination.
- Most consumers in the US accept crop biotechnology, particularly when they understand its benefits.

Background

A discussion of crop biotechnology can best start by reviewing conventional agriculture and what humankind has done with the food supply for thousands of years because it creates a context within which to talk about biotechnology. It is important to recognize that we have been genetically modifying the food supply for thousands of years. We have been using techniques like conventional breeding, radiation breeding, and wide crosses to improve the food supply.

For decades plant breeders have had active programs of crossing wild relatives of vegetable varieties with commercially available varieties. The goal is to access different genetic background material that might provide, for example, disease resistance in varieties that will ultimately become commercialized. It is interesting to compare the original ancestor of corn, teosinte, with hybrid seed corn. Teosinte has a very small cob with only a few kernels. The dramatic differences when compared to modern field corn have been achieved using conventional breeding methods (Fig. 1). So humankind has been significantly altering the genetics of our food supply since we domesticated plants thousands of years ago.

Radiation also has been used in breeding for several decades [1]. Using a cobalt 60 gamma source, seeds are irradiated to create mutations in the DNA. Improved varieties are then selected. Since 1970 more than 1,800 different crop varieties have been developed using radiation mutagenesis [2]. It is important to understand that plants improved through conventional genetic modification, including radiation breeding, undergo no governmental food or environmental safety review prior to being introduced into the marketplace. For example,

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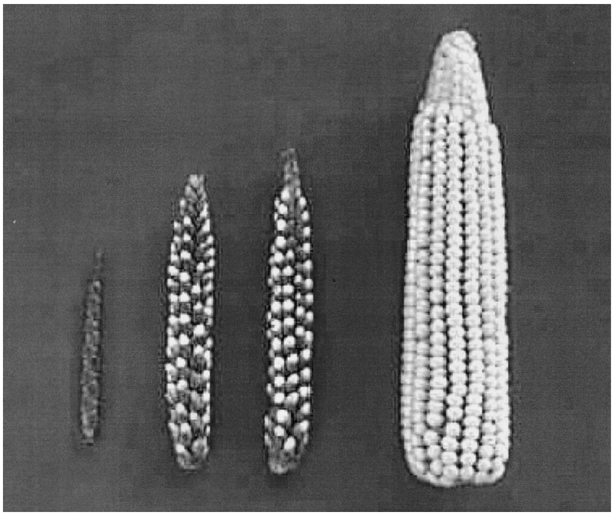

Fig. 1. Teosinte *vs.* modern hybrid field corn.

when new varieties of sweet corn are developed, FDA, EPA or USDA does not review them before introduction into the market. We rely on informal processes conducted by breeders, farmers and food processors to identify unusual mutations generated by conventional breeding methods.

Traditional Breeding *vs.* Genetic Modification

Genetic engineering of crops became available in the early 1980's as genetic engineering techniques were being perfected. The advantage of genetic engineering is that it allows the transfer of a single gene, or a couple of genes, in a much more precise, controllable and predictable way than is achievable with conventional breeding. Conventional breeding involves random mixing of the tens of thousands of genes present in a plant with the ten of thousands of genes present in another plant. In contrast, genetic engineering is a much more precise way of improving crops. Improvements can be achieved in much shorter time frames. In the past, it took 10 to 15 years to introduce a new variety of sweet corn. This time has been cut in half using the tools of genetic engineering. In addition, genetically engineered crops are required to undergo extensive food and environmental safety assessment, whereas conventionally modified crops are not.

One could ask why do we need biotechnology when we have been making incredible achievements in our food supply using conventional methods. To answer that question, we have to realize that, today, over 800 million people face daily hunger; furthermore, a majority of the global population growth in the next 50 years will be in developing countries where malnutrition is already prevalent. Forty percent of the world's land use for agriculture is already seriously degraded. In order to meet the nutritional needs of this growing population, cereal production alone will need to increase by 40% in the next 20 years. We simply cannot achieve the kinds of yield increases in a sustainable way using traditional methods of breeding. Biotechnology is an important tool in addition to all of the other tools to produce a food supply that will be sustainable in the long run and will be able to meet these needs in the future [3,4].

Benefits of Genetically Modified Crops

Almost all of the world's major crops are now being improved using genetic engineering, although initial efforts have focused on commodity crops—primarily corn, soybeans, cotton, canola and potatoes. However, there are many other crops, including other cereal grains and a number of vegetables and fruits, that have been improved using genetic engineering and are in the commercialization pipeline (Table 1) [5].

Biotechnology crops are the most rapidly adopted technology in the history of U.S. agriculture. The first genetically modified crops were commercially grown in 1996 [6]. USDA estimates for 2001 indicate that about 25 million acres (20% of global total) of corn, 82 million acres of soybeans (63%), 7 million acres of cotton (13%) and 3 million acres of canola (5%) grown globally are genetically modified varieties [7] (Fig. 2). And FDA has approved 51 different products that are in various stages of commercialization [8].

One of the first products of plant biotechnology was insect resistant corn. A single gene encoding an insecticidal protein from *Bacillus thuringiensis* (Bt) was transferred into corn. The Bt gene confers resistance to the European corn borer, a devastating insect pest [9]. In addition to the European corn borer, corn earworm is another problem in sweet corn, and both need to be controlled. Consumers typically throw away ears of sweet corn if they find worms, even though the heavy use of pesticides assures that the worms do not survive more than about an inch down the cob. Consumers who find worms in their frozen or canned corn are sure to register complaints with the company. To avoid these problems, growers, particularly in the southern states that grow two or three crops of corn each year, may spray sweet corn up to 60 times in a season to control these pests. Adoption of this technology would result in a higher quality product and significant reduction in the use of pesticides.

Although the European corn borer and corn earworm have the word "corn" in their names, they affect many other vegetables, such as green beans and peppers. The same Bt gene in field corn can be transferred into other vegetables and confer resistance to those same, or related, insect pests. The Bt gene has been transferred into potatoes to confer resistance to the Colorado potato beetle, a devastating pest in potatoes [10]. The leaves of conventional potato plants are almost totally denuded by the Colorado potato beetle, and this lowers crop yields. The Bt gene also has been transferred into cotton. The cotton boll in genetically modified cotton is protected from the cotton boll weevil; thus, yields are significantly higher. Cotton and potato crops receive extensive pesticide treatment in the United States, and use of the genetically modified varieties results in a reduction in pesticides [11].

Table 1. Types of Crops Genetically Modified with Quality Traits and Approved for U.S. Field Tests Through 2001 [5]

Crop	Quality Characteristic
Alfalfa	Decreased lignin, delayed ripening
Apple	Sugar alcohols increased, altered ripening, carbohydrate metabolism altered
Barley	Heat stable enzymes, novel protein, storage protein altered, disulfide bonds reduced, digestibility improved
Broccoli	Prolonged shelf-life
Canola	Altered fatty acid profile, increased lysine, altered amino acid composition
Carrot	Improved nutrition
Cassava	Improved nutrition
Coffee	Delayed ripening, reduced caffeine
Corn	Altered carbohydrate metabolism, increased methionine, lysine and tryptophan, altered amino acid composition, improved protein quality, altered oil profile, decreased phytate, decreased lignin, increased phosphate, anthocyanins in seeds, mycotoxin production inhibition
Cotton	Improved fiber strength and quality
Grape	Improved fruit quality
Lettuce	Brown spot resistance, delayed senescence
Melon	Delayed ripening
Papaya	Delayed ripening
Pear	Altered ripening
Peppers	Delayed ripening, increased shelf-life
Pineapple	Increased sweetness
Plum	Delayed ripening
Potato	Increased solids, increased carbohydrates, improved nutritional quality, increased tyrosine, altered amino acids, black spot bruise resistance, decreased glycoalkaloids
Rice	Increased starch, altered protein storage, novel protein produced
Soybean	Improved protein quality, increased methionine, lysine, improved animal feed quality, novel protein introduced, altered oil quality, increased phytosterols and phytostanols, fumonisin degradation
Strawberry	Delayed ripening
Sunflower	Altered storage protein, animal feed quality improvement
Sweet potato	Altered amino acid composition, protein quality improved
Tomato	Delayed ripening, increased starch and solids, altered sugar profile, pigments altered, fruit size enlarged, altered carotenoid content, altered processing characteristics, protein quality altered, increased antioxidant enzymes
Wheat	Storage protein altered, improved digestibility, increased methionine, nutritional quality improved, novel protein introduced

The second major area of genetic modification is herbicide tolerance. Herbicide tolerant crops are tolerant to the more environmentally friendly herbicides, for example, glyphosate. Glyphosate and other broad-spectrum herbicides eliminate a variety of weeds, so the farmer can use one product instead of several different chemicals. These products also significantly reduce crop injury, and, because they degrade quickly in the soil, farmers can be less concerned about crop rotation [12]. One of the most valuable aspects of these products from an environmental perspective is that they encourage "no till" farming methods, which significantly reduce soil erosion [13].

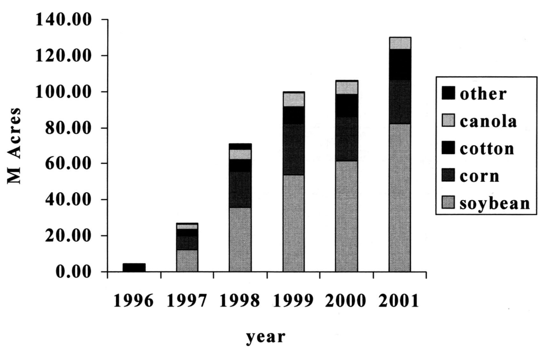

Fig. 2. Acres of approved genetically modified crops planted worldwide, 1996–2001. Adapted from [7].

The vegetable processing industry would value the same herbicide tolerance in sweet peas. Weeds growing in pea fields are harvested along with the peas. Pea fields are frequently contaminated with "nightshade," a weed that has a berry the same size, color and density as peas. When these berries are thermally processed along with the peas, the berries harden and are highly unacceptable to consumers. Farmers have a hard time eliminating nightshade from their pea fields; herbicide tolerant sweet peas would simplify weed control and improve final product quality.

Farmers have recognized the benefits of crop biotechnology and have readily adopted it. Use of these crops has resulted in environmental and food safety benefits, including a significant 2.7 million pounds per year reduction in the use of pesticides [11], and modeling studies indicate that ground water contamination by herbicides can be significantly reduced when glyphosate tolerant crops are planted [14]. An additional benefit of Bt corn is that, because the worms cannot form holes in the corn, fungi that can produce toxic mycotoxins, e.g., fumonisin, cannot attack the corn, resulting in a cleaner, safer product [15,16].

Safety

Only since the introduction of genetically modified crops have there been requirements to undergo extensive food and environmental safety evaluations prior to commercialization [17]. Companies developing such new products have submitted the results of their evaluations to regulatory agencies in the US and internationally to obtain clearance to market their products. Furthermore, scientific organizations around the world agree that genetically modified crops currently in use are not inherently less safe than conventional crops [18–22]. For example, breeders have developed via traditional breeding herbicide tolerant and pest resistant crops that have been grown for more than 20 years. These crops have never undergone any environmental safety testing. In many cases, they contain the same kinds of genes used in biotechnology-improved crops. The types of risks are the same for genetically modified and conventionally produced crops, and the extensive safety assessments provide equal, or greater, assurance of safety for genetically modified varieties. In over 400 million acres of genetically modified crops planted worldwide [6], there has been no confirmed adverse report to date.

In the United States, all 51 of the genetically modified products reviewed to date have been determined to be substantially equivalent to their conventional counterpart, and no special labeling is required. These commodity crops have made their way into literally thousands of ingredients used in processed foods today. Examples of soy-derived ingredients include soybean oil, lecithin, soy protein isolates and mono- and diglycerides. Examples of corn-derived ingredients include corn oil, cornstarch, corn flour, cornmeal, dextrose, and high fructose corn syrup. Lecithin is a major component of chocolate, and mono- and diglycerides are processing aids used in numerous dough and bread products. High fructose corn syrup is used extensively in the beverage industry. It has been estimated (G. Grabowski, Grocery Manufacturers of America, Washington, D.C., personal communication) that over 70% of all processed foods contain at least one ingredient that could have been derived from genetically modified soy or corn.

Consumer Acceptance of Labeling

While there is concern among some Europeans about genetically modified products, U.S. consumers on the whole appear to be much less concerned. The food industry has been collecting consumer sentiment data for over five years, and the number of calls about biotechnology to food manufacturers remains very small. According to a recent survey by the International Food Information Council, consumer awareness of genetically modified foods is increasing with over 74% of consumers aware or somewhat aware of genetically modified foods [23]. However, most Americans are not aware that the vast majority of processed foods in the marketplace contain ingredients from genetically modified crops. About half of consumers are supportive of the technology, and the remainder are either not supportive or don't know. If unsure consumers and those against the technology are provided a simple explanation of biotechnology, support increases dramatically; therefore, education is important for acceptance of the technology. The number one reason people support genetically modified foods is reduction in use of pesticides, and information about this benefit needs broader dissemination.

Labeling of genetically modified products is a controversial issue [24]. If consumers are asked what is important to them on a food label, the presence of genetically modified ingredients is not a priority [23]. This may be due to lack of awareness, but consumers indicate repeatedly that simply labeling products as being genetically modified does not provide enough information. The labeling schemes present in Europe today require statements such as "genetically modified organism," but this is not enough information for U.S. consumers. They prefer to ask, "Why was it modified?" "How was it modified?" "What is the benefit?" So it becomes a challenge for food manufacturers to fit such educational information on a label. Instead of labeling biotechnology-derived ingredients, consumers say they want more details through toll-free numbers, through brochures that are available in the supermarket or to be able to go to a web site that can give them more information on this topic.

Some US companies have decided to label their products as "non-genetically modified" or "GMO-free." On April 5, 2001, the *Wall Street Journal* reported on the accuracy of GM label claims on 20 of those products. Sixteen of the 20 products labeled as "non-genetically modified" or "GM-free" actually tested positive for the presence of genetically modified ingredients. In one case, 40% of the soy in the product was genetically modified, even though it was labeled as "non-genetically modified".

Most food companies are using genetically modified ingredients for domestic production. While they have confidence in the safety of the product, they lack confidence in commodity agriculture's ability to deliver identity-preserved ingredients. As was shown in the investigation conducted by the *Wall Street Journal*, even under the best conditions of identity preservation the majority of products tested positive for genetically modified ingredients. An additional complicating factor is that current GM testing methodologies are inadequate [24]. It is not uncommon to have unacceptably high levels of false positive and false negative results. This lack of reliable detection methodologies creates a significant challenge for the food industry.

The potential requirement to "identity preserve" genetically modified from traditional commodity crops also creates enormous problems. Our current agricultural system lacks separate storage, processing, labeling and transportation capabilities because the food processing system has been built at the tail end of the commodity agriculture system. This could result in potential mislabeling and liability issues.

The labeling and identity preservation issues could become irrelevant when the next generation of biotechnology products with compelling consumer benefits starts appearing. There are some exciting products in the pipeline that will result in removing allergens from foods and improving taste, texture, aroma and keeping-quality of fruits and vegetables [25]. The levels of many health-promoting phytochemicals could be enhanced using genetic engineering. Even though Golden Rice will not be available for four to five years, the potential nutritional benefits of this product are very significant, particularly in developing countries.

Conclusions

Crops developed via biotechnology have been on the market for only six years but have had an enormous impact on our food supply and on modern agriculture. Unlike crops developed via traditional breeding, crops developed via biotechnology undergo extensive safety testing. It is notable that while about 70% of processed foods on the market today in the US contain at least one ingredient from a genetically modified crop, there has not been a single documented case of an adverse health experience. Farmers have recognized the value these products provide, including decreased reliance on pesticides, increased yield, no-till farming practices and improved product quality. Since their introduction, farmers have continued to increase plantings of genetically modified crops. Although some consumers have expressed and continue to express concerns about the technology, most Americans accept it, particularly when they understand its benefits. Over the next several years, crop biotechnology will be applied to the development of crops important to the expanding populations of the developing world. In addition, crops with enhanced nutritional properties and even containing vaccines will appear over the next five to ten years. Such products should further enhance consumer acceptance of this new technology.

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