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Current and future benefits from the use of GM technology in food production

K.-H. Engel *, Th. Frenzel, A. Miller

Technische Universität München, Lehrstuhl für Allgemeine Lebensmitteltechnologie, Am Forum 2, D-85350 Freising-Weihenstephan, Germany

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Abstract

For the current generation of genetically modified (GM) crops the improvement of agronomic traits (e.g. herbicide tolerance, insect resistance) has been a major objective. The lack of obvious and direct benefits for the consumer has been a main point of criticism. Future trends will increasingly encompass the modification of quality traits, such as the improvement of sensory and especially nutritional properties. Some of the ongoing developments try to meet the desire of consumers for ‘healthy’ or ‘high-tech’ foods in developed countries. Others are intended to assist in adjusting the nutritional status of foods to the needs of consumers in developing countries. Considering the increasing world population and the limited amount of arable land, GM technology may also become a valuable tool to ensure food security. The major prerequisite for the applicability of the technique is the safety of the resulting products. The increasing complexity of modifications intended might require adjustments and improvements of the strategies applied to the safety assessment of GM foods. Present research activities try to meet these new challenges. © 2002 Published by Elsevier Science Ireland Ltd.

Keywords: Genetically modified crops; Food safety assessment

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1. Introduction

Within a rather short period of time genetic engineering has evolved from basic science to commercial applications. The use of this versatile tool of modern biotechnology has become a multibillion-dollar business (Malik, 1999). Considering the important role of fermentation technology in traditional food production, it was not surprising that the area of foods and food ingredients attracted the interest of genetic engineers from the very beginning. One of the first commercial examples was the production of the cheese-making enzyme chymosin, traditionally obtained from calves, by fermentation using genetically modified (GM) microorganisms (Flamm, 1994). The techniques developed for transformations of plants were readily applied to crops and GM plants used for food production are now a reality (James, 2000).

Starting from 1.7 million ha in 1996, the global area of transgenic crops significantly increased to 44.2 million ha in 2000. However, interpretation of these total numbers has to take into account

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* Corresponding author. Fax: +49-8161-714259.

E-mail address: k.h.engel@lrz.tu-muenchen.de (K.-H. Engel).

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that present applications of recombinant DNA techniques focus on few plants and few traits. The spectrum of commercialized transgenic crops is essentially limited to soybean, corn, cotton and canola. Ninety-three percent of the GM crops planted exhibit herbicide tolerance and insect resistance as target traits (James, 2000). These applications may be useful to the growers but they seem of no direct and obvious benefit for consumers. This is one of the reasons for the low acceptance of foods derived from genetically modified organisms (GMO) and the continuing public debate on this technology.

The objectives of this contribution are: (i) to review the current and potential applications of GM in food production; (ii) to outline present and future benefits of GM crops; and (iii) to discuss challenges in safety assessment evolving from new developments in this field.

2. Applications

2.1. Agronomic traits

2.1.1. Herbicide tolerance

The application of herbicides is an indispensable part of modern agriculture. If weeds are not controlled, they may account for crop losses ranging from 20 to 60%. Tolerance of crops to herbicides has been achieved either (i) by introducing a gene coding for a target enzyme insensitive to the herbicide (Padgette et al., 1996) or (ii) by introducing a gene encoding an enzyme metabolizing and thus detoxifying the herbicide (Rasche et al., 1995).

Tolerance to glyphosate (Roundup Ready) and glufosinate (BASTA), respectively, are the commercially most relevant applications. Herbicide-tolerant plants are grown on 74% of the global area of transgenic crops. Herbicide-tolerant soybean was the most dominant (59%) transgenic crop grown in six countries (USA, Argentina, Canada, Mexico, Romania and Uruguay) in 2000 (James, 2000).

Major benefits of growing herbicide-tolerant crops are increased yields and reduced costs. Moisture loss and soil erosion can be minimized by non-tillage farming. Roundup Ready and BASTA are favorable in terms of mammalian safety and environmental properties (Padgette et al., 1996).

2.1.2. Insect resistance

The commercially second most important trait conferred to crops by genetic engineering is insect-resistance. Plants expressing δ-endotoxins from *Bacillus thuringiensis* (Bt) have been grown on 19% of the global area of transgenic crops (James, 2000). This strategy has been applied to confer insect-resistance to crops such as canola, corn, cotton and potato. Major benefits exhibited by Bt-resistant plants comprise improved crop yields, reduced use of chemical insecticides (Xia et al., 1999), reduced levels of fungal toxins (Munkvold et al., 1997) and preservation or enhancement of populations of beneficial insects (Betz et al., 2000).

In order to minimize the development of resistance to Bt toxin, field management practices such as maintenance of refuges are applied (Mandaokar et al., 1999).

Alternative strategies to confer insect resistance to plants, which might become of practical importance in the future have been described (Schuler et al., 1998). They include the expression of lectines (Down et al., 1996), proteinase inhibitors (Leplé et al., 1995), α-amylase inhibitors (Altabella and Chrispeels, 1990) or cholesterol oxidase (Cho et al., 1995).

2.1.3. Resistance to viruses, fungi and bacteria

Protection against viral diseases has been achieved by expressing viral coat proteins or by introducing viral replicase genes (Galun and Breiman, 1997). Resistance to fungi is conferred by GM-induced biosynthesis of phytoalexins, by the expression of cell wall-hydrolyzing enzymes (chitinases, β-glucanases) or expression of ribosomal inhibitor proteins specific to fungal ribosomes (Malik, 1999). Resistance to fungi is beneficial not only from a commercial point of view (yield) but also considering the reduction in mycotoxin levels. Various strategies ranging from expression of antibacterial enzymes (Düring, 1996) to engineered detoxification (Zhang, 1999) have been described to confer resistance to bacteria.

The present improvements of agronomic properties are tailored to the needs of agriculture in developed countries. Traits such as pest- and disease-resistance are also of outstanding importance to developing countries. This becomes very evident if one considers that more than 15% of the world's crops are lost by insect damage and this happens mostly in developing countries. However, in order to contribute really to food security, biotechnological developments will have to focus on crops important in developing countries, e.g. cassava and rice (Puonti-Kaerlas et al., 1999).

2.1.4. Other agronomic traits

Additional strategies to improve crop productivity especially in developing countries are based on increasing crop tolerance to abiotic stress as evoked by the rough environmental conditions.

2.1.4.1. Drought resistance. The expression of the full genetic potential of a plant (e.g. maximum yield) is seriously affected by the inadequacy of water. Pathways involving the biosynthesis of metabolites like polyamines, proline, glycine betaine and trehalose were shown to be related to drought resistance (Mitra, 2001).

2.1.4.2. Effects of metals. Thirty percent of arable land is characterized by the poor solubility of iron due to the alkaline soil. The resulting limitation of plant growth cannot be alleviated by fertilizers. The tolerance of rice to such low iron availability in alkaline soils could be improved by genetically engineering the crop to release more iron-solubilizing chelators (Takahashi et al., 2001).

Aluminum released by acid soils is toxic to crop roots. Thirty to forty percent of the world's arable land is affected by acid soils resulting in yield losses of up to 80%. Expression of bacterial citrate synthase in roots is one of the strategies presently being developed to overcome this problem (De la Fuente et al., 1997).

2.1.4.3. Salinity. Forty percent of the irrigated land is affected by salinity. The resulting decline in photosynthesis and the increased formation of oxygen radicals limits the crop performance. Genetic engineering can be used to increase the cellular content of osmolytes (Karakas, 1997), to express antioxidative enzymes (Van Breusegem et al., 1999), or to introduce sodium pumps (Apse et al., 1999).

2.2. Quality traits

In industrialized countries the improvement of the agronomic performance of crops does not appear as a direct benefit to the customer purchasing the food in the super market. In order to convince the consumer on the advantage of genetic engineering and thus to increase the acceptance of GM foods, 'obvious' traits such as sensory or nutritional properties have to be improved.

2.2.1. Sensory properties

The FLAVR SAVR™ tomato, the first transgenic crop put on the market in the US (Redenbaugh et al., 1995) exhibited delayed ripening due to anti-sense inhibition of polygalacturonase, a key enzyme involved in the softening of cell walls. Unfortunately, this trait was mainly propagated as a means to increase the shelf life of tomatoes. The potentially positive effect on the flavor implied in the commercial name has actually not been exploited. Other strategies trying to improve the flavor characteristics interfere with the metabolism of ethylene, e.g. by anti-sense inhibition of the 1-aminocyclopropane-1-carboxylic acid oxidase via anti-sense (Ayub et al., 1996). Approaches that are more recent are intended to modify enzyme-catalyzed steps in the biosynthesis of specific flavor and aroma constituents. Examples are the genetic engineering of essential oil production in mint (Lange and Croteau, 1999) or the modification of lipoxygenase (Griffiths et al., 1999) and alcohol dehydrogenase (Prestage et al., 1999) involved in the formation of C_6-compounds by degradation of unsaturated fatty acid precursors. Considering the role of biotechnology in the production of flavors (Krings and Berger, 1998), the use of modified microorganisms (Rijnen et al., 2000) will be of an increasing importance.

2.2.2. Nutritional properties

The next wave of applications of recombinant DNA techniques in food production will be characterized by approaches to improve the nutritional properties of raw materials and the foods made thereof (Kochian and Garvin, 1999). Genetic engineering can be applied to modify macronutrients as well as micronutrients in foods.

2.2.2.1. Macronutrients. Genetic engineering of lipid metabolism in oil crops is being driven by the demand for oils and fats as raw material for the chemical industry as well as by the key role of edible fats and oils in the human diet (Gunstone, 1999; Murphy, 1999). Modification of the chain lengths and the degree of saturation of fatty acids has resulted in commercialized products, such as high laurate canola oil (Del Vecchio, 1996; Friedt and Lühs, 1998) and sunflower seed oil with high oleic acid content (Kinney and Knowlton, 1998). Designing the lipid content of edible oils according to health benefits will be one of the major trends in the near future (Vageeshbabu and Chopra, 1999).

Various strategies have been described to improve the protein quality of foods and feeds (De Lumen et al., 1997; Roller and Harlander, 1998). This ranges from functional properties, e.g. baking quality of wheat (Vail and Anderson, 1997; Anderson and Blechl, 2000), to nutritional properties, e.g. enhancement of the content of essential amino acids. The attempt to increase the methionine content of soybeans by expressing a protein from Brazil nut resulted in the unintended transfer of the allergenic protein (Nordlee et al., 1996). On the other hand, enzyme inhibition via antisense technique may also be applied to reduce the allergenic potential of crops as demonstrated for rice (Tada, 1996).

Modern plant biotechnology has focused very early on the genetic modification of plant carbohydrate metabolism (Petersen et al., 1995). Influencing source–sink interactions, improving starch biosynthesis, changing starch composition or accumulating fructanes in transgenic crops are examples for relevant applications (Turk and Smeekens, 1999).

2.2.2.2. Micronutrients. The wide range of isoprenoids found in plants and the integration of metabolic pathways of steroids, carotenoids and retinoids (Gawienowski, 1999) offers the potential to influence the content of these compounds by genetic engineering. An exciting current example is the genetically engineered biosynthesis of β-carotene in the so-called 'Golden Rice' (Ye et al., 2000). The presence of this provitamin in a major food might help prevent vitamin A deficiencies in considerable parts of the population in Southeast Asia.

Overexpression of γ-tocopherol methyltransferase in *Arabidopsis* seeds demonstrated the potential to shift the tocopherol distribution in oil in favor of the desired α-tocopherol, the essential component (vitamin E) in mammalian diets (Shintani and DellaPenna, 2000).

It has been estimated that about 1.3 billion people suffer from iron deficiency. In order to increase the iron content of rice, the major staple food in Asia, three approaches have been proposed: (i) introduction of the ferritin gene from *Phaseolus vulgaris* into rice; (ii) expression of a heat-tolerant phytase from *Aspergillus fumigatus*; and (iii) overexpression of endogenous cysteinrich metallothionein-like protein (Lucca et al., 2000).

Owing to the present wave of 'functional foods' increasingly put on the market in Western countries, there is increasing interest in bioactive plant constituents. Modifying composition and distribution of high-value compounds, such as carotenoids and vitamins (Hirschberg, 1999) or flavonoids and isoflavonoids (Mounts et al., 1996; Dixon and Steele, 1999) may become 'gold mines' for metabolic engineering.

2.3. GM microorganisms

Owing to the important role of fermented foods in diets all over the world, microorganisms are ubiquitously applied to food production and preparation. By means of genetic engineering, the properties of microorganisms, e.g. starter cultures, can be changed more precisely than by random mutagenesis and subsequent selection procedures based on classical bacteriological and genetic methods. Major goals are optimization of the production process, improvement of product quality and safety (hygienic status) and enlargement of product diversity (IFT, 2000).

The broad spectrum of fermentation processes applied in food production and the important role of microorganisms in functional foods (e.g. probiotics) demonstrate the enormous potential of genetic engineering for improving microorganisms used in food industry. GM microorganisms will be used to produce enzymes with optimized properties regarding activity, specificity or stability (Roller and Goodenough, 1999).

2.4. GMO as bioreactors

Genetic engineering will indirectly open the way for many new technologies. In addition to microorganisms, plants and animals will be increasingly seen as 'bioreactors' enabling the production of broad-spectrum food ingredients, food additives or food contact materials. These may either be 'nature-identical' or 'tailor-made' in order to meet the needs of a certain product specifically. The strategy to express enzymes involved in the conversion of starch to fructose and normally used in the technological process in the potato tuber is an example of the developments to be expected in the future (Beaujean et al., 2000).

3. Food safety assessment of GM crops

3.1. Present approaches

The principle of 'substantial equivalence' elaborated in several international consultations since the beginning of the 1990s (WHO, 1991, 1995; OECD, 1993) became a key element in the safety assessment of foods derived from GMO. The concept is used to identify similarities and differences between the GM food and a comparator with a history of safe use that subsequently guides the safety assessment process (WHO, 2000). It proved to be suitable for the first generation of GM crops. Foods consisting of or containing GMO belong to the best-analyzed foods we know. So far, there are no documented reports on adverse effects on humans resulting from the consumption of food produced by means of recombinant DNA techniques. Nevertheless, the safety assessment approach is subjected to criticism and controversial discussion. Contemporary and future activities have to take arguments forwarded into account and contribute to the development of science-based adjustments and improvements, especially in the light of the next generation of GM foods to be expected.

3.2. Future challenges

As outlined in the above sections, the next generation of GM foods will not be limited to plants with agronomic advantages but will increasingly focus on improvements of the nutritional properties of a crop. These GMO with 'added values' will cross the borderline between GM foods and 'functional foods'.

The complexity of metabolic changes in GM crops will increase. The establishment of 'substantial equivalence' to a counterpart with an accepted standard of safety will become more difficult. Therefore, the need to perform comprehensive safety and nutritional assessment of 'novel foods' will increase. As feeding studies with whole foods will be requested more often, a refinement of these approaches will be needed. The development of early in vitro/in vivo biomarkers for toxicity might be useful.

The safety assessment of GM foods will have to go beyond the assessment of the single product as such and will have to encompass the overall impact of the food to the nutritional status of the population. The assessment of the intake of critical nutrients will be of increasing importance. The different situations in developed and developing countries will have to be taken into account.

3.3. Examples for current research activities

In the course of the fifth framework program the EU Commission financially supports research projects related to the safety assessment of GM foods. They cover subjects such as: (i) 'New methods for safety testing of transgenic food' (SAFOTEST, QLK1-19999-00651); (ii) 'New methodologies for assessing the potential of unintended effects in GM crops' (GMOCARE, QLK1-19999-00765); (iii) 'Safety evaluation of horizontal gene transfer from GMO to the microflora of the food chain and human gut' (GMOBILITY, QLK1-19999-00527); and (iv) 'Reliable, standardized, specific, quantitative detection of GM foods' (QPCRGMOFOOD, QLK1-19999-01301).

Cluster coordination of the projects is achieved through the European Network: 'Safety Assessment of Genetically Modified Foods' (ENTRANSFOOD). In this thematic network four working groups related to the research projects have been established in which contributors from academia, industry, regulatory organizations and consumer groups elaborate reviews, position papers and integrated evaluation documents and prepare recommendations and research proposals related to the safety assessment of GM foods.

4. Outlook

Considering the expected increase in world's population, food security will be one of the major social issues in the coming decades. Food production will have to be at least doubled to meet the needs. The potential of genetic engineering to assist in meeting this challenge is far from being fully exploited. For example, cereal grains (mainly wheat, rice and maize) account for approximately half of the calories consumed by humans. However, the practical use of transgenic cereals is still in its infancy (O'Brien and Henry, 2000).

Nearly 70% of poor and food-insecure people live in rural areas in developing countries. Low production in agriculture is a major cause of poverty, food insecurity and poor nutrition. Genetic engineering can help: (i) facilitate agricultural and rural growth through high-yielding varieties resistant to biotic and abiotic stresses; (ii) reduce pest-associated losses; (iii) support environment-friendly production technologies; and (iv) enable precision agriculture, i.e. use of right inputs at the right time (Sharma et al., 2001). However, in order to achieve these goals, the application of genetic engineering has to be adapted to the specific issued related to local crops in developing countries (Atkinson et al., 2001; Herrera-Estrella, 2000; Wambugu, 1999). Recombinant DNA techniques should be increasingly used to improve the nutritional status of crops essential for the population in developing countries.

In industrialized countries the global area of transgenic crops has been reaching a plateau phase (James, 2000). Despite its obvious and broad potential (Halford and Shewry, 2000; IFT, 2000; Uzogara, 2000), consumers are increasingly reluctant to accept the technology as a standard tool in modern food production. Maybe the desire for health-promoting or disease-resisting food (functional food) and the possibility to use genetic engineering for these targeted improvements, will eventually pave the way for broader acceptance.

The discussion on the application of recombinant DNA techniques should be actively used for science-based education of consumers on traditional procedures applied in the production of foods. Difficulties in convincing consumers about the advantage of applying genetic engineering are very often due to idealized and unrealistic opinions on the classical methods (automatically considered as safe) used in conventional food production. Transparency in traditional food processing as well as in the application of modern techniques would help in increasing the understanding, and eventually also contribute to food safety.

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