Developing Fields in Food Biotechnology - the Potential of Higher Plants

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Summary

This article presents an overview of plant biotechnology at a time when there is considerable public debate over the launching of several transgenic crops and their by-products for retail sale and food processing.

Introduction

In the period leading up to 2020 to 2025, a range of international bodies project that the world's population will grow to 8-8.5 billion, leading to an enormous increase in food demand, stretching the known limits of productivity of cultivated land, itself a precious but diminishing resource.

Estimates prepared by the Population Reference Bureau indicated that by mid-1995, the world's population was 5,702 million, representing an increase of approximately 88 million over 1994. The annual rate of population increase declined to about 1.54% in 1995 from 1.6% in 1994, a result of birthrate declines in both Less-Developed Countries (LDCs) and More-Developed Countries (MDCs). If the 1995 growth rate were sustained, the world's population would double within 45 years. More than 85% of the population growth in MDCs occurred in the USA. In 1995, 32% of the world's population was below the age of 15, but the figure was 38% in LDCs outside China. Only 5% of the population in LDCs was over the age of 65 compared with 13% in MDCs. Urbanisation trends continued, with 43% of the total population living in urban areas; in LDCs 35% of their population was classified as urban compared with 74% in MDCs. The share of world population growth occurring in LDCs increased to 98% in 1995, and child-bearing females of LDCs were averaging about 3.5 children each during their lifetimes, a figure slightly more than double that of MDCs.

The UN Food and Agriculture Organization (FAO) Food Outlook report for 1995 estimates that during 1995-1996, the total shipment of food-aid in the form of cereals was 7.6 million metric tons (mmt, or million tonnes) declining from 8.4 mmt in 1994 - 1995, and from 12.6 mmt in 1993 - 1994. Much of the decline during this period was attributable to reduced releases from the USA. Further analysis shows that not all food-aid shipments were directed to the countries most in need: 10% less food-aid in 1994-1995 was received by the officially classified low-income (average annual income below $1345 in 1993) food-deficit countries. To solve poverty is to solve the problem of feeding people.

Inordinate strains will be placed on the less-developed countries for food, water, shelter, fuel, education and welfare. Large parts of Africa, especially, face dismal prospects. Access to the media and advanced medicine, though, will ensure that all citizens will demand improving quality of life regardless of local economic situations. Low-grade grazing systems coupled to poor, unsustainable agricultural systems will inexorably lead to the acceleration of deforestation, soil erosion, desertification and the rapid loss of natural and managed ecosystems, destroying genetic and environmental diversity. Social instability, emigration and trade disruption seem inevitable for the poorer of the less-developed countries.

Most reference to economic analyses in agriculture and horticulture relate simply to gross traded values of commodities, hectares grown, yield estimates, major categories of land use, imprecise crop and livestock categories, unit prices, direct employment and percentage origin of Gross Domestic Product. Data relating to (i) processing values for the food and non-food sectors; (ii) development and maintenance of rural, industrial and marketing infrastructures; (iii) amenity and tourism; (iv) influence of subsidies; (v) costs of import substitution; (vi) assessments of trends in and prospects for exports and trading; (vii) relative social values to the national and local economies; (viii) cultivar performance and market share; and (ix) indirect employment, are usually ignored because they are often unreliable, incomplete, out of date, anecdotal, disputed or subject to commercial secrecy. International comparisons are made especially difficult by variations in the methods and dates of sampling, unspecified types of analyses and fluctuating currency exchange values.

It seems remarkable that there is so little publicity given to the loss of cultivated land throughout the world. Soil erosion, pollution, buildings, roads, airports, and recreation facilities account for the main loss of productive land. Modern monocultural agricultural systems can cause problems, *eg* use of xenobiotics, soil compaction and erosion, salinity effects and changes in the soil flora and fauna, but traditional methods (*eg* slash-and-burn, uncontrolled grazing) can be even more erosive without even being productive. All too frequently, third-world agriculture can incorporate many of the bad practices of high-input agriculture now being phased out in the western world. About 85% of the growth in population occurs in developing countries where the numbers of malnourished people have increased by 35% since 1980. In the tropical zones, the area of cultivated land per capita has declined from 0.28 ha in 1971 to 0.22 ha in 1986; this figure masks urbanisation, fragmentation of farms, and expansion of cultivation into virgin lands unsuitable for arable farming in the medium term.

Given that the area of land under cultivation is a limited resource and difficult to increase without massive migrations of people and devastation of forests, that pests and diseases have a phenomenal ability to circumvent control measures, the global picture is far from bright until the demand of the world population matches sustainable resources.

One possible or probable scenario is that the industrially under-developed - or low income - world will become the major source of manufactured goods, effectively reversing the trend in trade established since the Industrial Revolution (Carruthers, 1993). The economies of most of the countries of the Pacific rim are buoyant, and in Asia there are several countries with sophisticated, urbanised workforces able to operate efficiently and compliantly with relatively low incomes. Scientific intercommunication, multinational trading, and improving education in the low-income world ensure that invention, intellectual property and service industries will not be the preserve of the present developed world. Moreover, agriculture in developing countries is no longer regarded as the engine of economic growth - witness the pressures on the Consultative Group on International Agricultural Research. Thus it is likely that most the of world's food production would take place in the temperate zones. Whether or not there would be the means to pay for the food is a moot point.

Conventional management of terrestrial and aquatic resources will not meet future demands. Over 90% of the world's population depend on just 15 plant and 7 animal species for food (Hillman, 1992); a tiny genetic reservoir to combat the ravages and vagaries of pests, diseases and inclement conditions. To this must be added the fact that as the only animal to cook food and thereby broaden the range of acceptable food species and types, mankind is faced in the arid and semi-arid regions of the developing world with a shortage of fuel for cooking.

Woody perennial species, *eg* fruit trees, present one of the stiffest challenges for crop management. New initiatives are desperately needed for breeding, selection, propagation and health of trees and shrubs.

UK Food Plants

The current range of home-grown and imported plants consumed in the UK is large (Table 1), although most are of minor importance and diets can be depressingly narrow. Advancements in modern retailing arrangements and marketing efforts, aided by changes in lifestyle and a massive increase in professional catering, all raise demands and expectations in the quality and type of food rather than quantity. Even though there are residual historical, ethnic, social and economic factors that favour specific diets, growing health awareness and hedonism have become incompatible with restricted, narrow supplies and regional seasonality of produce. Blemish-free and safe produce, meat and milk products are universal expectations of processors, retailers and consumers alike, and dominated by the perceptions of urban dwellers.

Table 1.

Range of food plants consumed in the UK

1. *Poaceae (Gramineae)*

The cereals - barley, oat, rice, rye, wheat **Coarse grains** - maize, sorghum **Forage grasses** **Sugar cane**

Grass fruits (caryopses or grain) are the largest single source of carbohydrate on earth

2. *Leguminosae*

Forage legumes **The pulses** - adzuki, blackgram, broadbean, chickpea, cowpea, haricot, horsegram, jack, kidney, lablab, lentils, lima, mat, mung, pea, pigeonpea, soya, string- and snapbean, sword, vetches, yambean

Proteinaceous, sometimes contain toxins, allergens or haemagglutinins. Also produce oils.

3. *Solanaceae*

Aubergine	**Potato**
Capsicum	**Tomato**

4. *Cruciferae*

Broccoli	**Kohl-rabi**
Brussels sprout	**Mustard and Cress**
Cabbage	**Oilseed rape**
Cauliflower	**Radish**
Chard	**Swede**
Chinese leaves	**Turnip**
Kale	

Proteins, oils and carbohydrates. The most important group of green vegetables.

5. *Chenopodiaceae*

Beet - fodder, garden, spinach, sugar
Mangold
Spinach
Swiss chard

6. *Liliaceae*

Chives	**Onion -** Egyptian, spring, Welsh
Garlic	**Rakkyo**
Leek	
Onion	

7. *Rosaceae*

Soft fruit -	blackberry, currant (black/red/white), gooseberry, hybrid berries, raspberry, strawberry
Stone fruit -	almond, apricot, cherry, damson, greengage, nectarine, peach, plum
Top fruit -	apple, medlar, pear, quince

8. *Cucurbitaceae*

Courgette/Zucchini	**Melon**
Cucumber	**Melon (water)**
Gourd	**Pumpkin**
Marrow	**Squash**

9. *Umbelliferae*

Carrot	**Parsley**
Celeriac	**Parsnip**
Celery	

10. *Major imported families*

Anacardiaceae	- mango, cashew
Araceae	- cocoyams, dasheen, yautia, taro
Bromeliaceae	- pineapple
Convolvulaceae	- sweetpotato
Euphorbiaceae	- cassava
Musaceae	- banana, plantain
Palmae	- date palm, sago palm, oil palm, betel nut
Rubiaceae	- coffee
Rutaceae	- citron, grapefruit, lemon, lime, orange, pummelo, tangerine
Sterculiaceae	- cocoa, cola
Theaceae	- tea

11. *Miscellaneous horticultural plants*

Artichoke	**Macadamia**
Avocado	**Mulberry**
Blueberry & cranberry	**Okra**
Breadfruit	**Papaya**
Chestnut	**Passionfruit**
Endive	**Pecan**
Fig	**Pistachio**
Grape	**Pomegranate**
Guava	**Rhubarb**
Hazelnut	**Tamarind**
Lettuce	**Walnut**

Also includes flavourings, fumatories, herbs and spices and masticatories.

In production terms, the agricultural and horticultural output of the UK reflects the constraints of land area and climate. Comparisons of production with Europe and the rest of the world (Ministry of Agriculture, Fisheries and Food Internet site http://www.open.gov.uk/maff/stats/) reveals that the UK arable and horticultural sectors were a small proportion of European production. A valuation of £6,798 million was given to the major UK arable and horticultural crops at 1995 prices. On the other hand, the industry was highly efficient. For wheat, barley, potatoes, cabbage, onions, carrots and tomatoes, for example, the crop yield on a kg per ha basis was considerably greater than the average for the rest of Europe or the world.

As a share of the UK economy in 1995, agriculture and horticulture constituted *circa* 1.5% of the Gross Domestic Product (GDP), approximately £9 billion, and forestry only 0.05%. These figures belied the importance of successful value-adding industries with larger GDP valuations, downstream and upstream, and were based on current market valuations of primary production. Perturbations to the supply and low costs of primary product would have dramatic effects on these secondary industries and commerce in general.

Plant Breeding

Central to the ability of the bulk of the population to move from food cultivation and harvesting to engage in social and technological advancement is the provision of improved crop plants throughout the ages. Plant breeders have always been involved in genetic engineering. Characters including yield performance, resistance or tolerance to pests and diseases, quality components, uniformity and lack of prolonged dormancy periods represent the main selection criteria.

Together with advances in automation, storage and processing there is a complacent view that plant breeding will perpetually answer basic nutritional needs for burgeoning populations. This is unacceptable.

Plant breeding programmes are protracted, expensive and are rarely allowed to proceed without interference. Basic to the needs of such programmes is access to genetic resources for parental material. Unfortunately, there has been severe attrition of genetic diversity by losses of diverse wild habitats, traditional farming area, valuable collections and obsolete landraces. Breeders need to screen vast numbers of clones over many years, carry out regional trials, multiply stocks, access statutory trials and be involved in marketing. Other problems faced include imprecise predictions of genotype by environmental interactions, incompatibility systems between and within species affecting the ability to cross-breed, juvenility or ripeness-to-flower phases, seasonal growth patterns, changing disease virulence patterns and disease vector distributions, and complex breeding objectives involving polygenic characters. Conventional plant breeding is well-established but needs to be supplemented by bioengineering technology to allow access to new sources of genetic variability, to speed up the process, to unravel the complexities of genomes (genetic constitutions), to understand the processes involved in breeding, and to improve the prediction of performance of products arising from the breeding programmes.

Plant breeders and geneticists, physiologists, biotechnologists, pathologists, agronomists and engineers, using advanced mathematics, chemistry and physics are providing new, improved, low-input cultivars with extended growing seasons, as well as better cultivation, protection, harvesting and storage technologies. This R&D combines fundamental, strategic and applied research approaches, usually within a single project. Natural tolerance or resistance to biotic and abiotic stress whilst sustaining quality, yield performance and efficiency of production are foremost in the minds of major companies and institutions, but to the intellectual challenges are added products for the rapidly expanding biotechnology, food processing and environment industries.

Engineering Plants

Modern technologies are reducing the reliance on a combination of serendipity and bulk selections for plant breeding and food processing qualities.

Aided by the rapid uptake of biotechnology in the higher education sector, and relatively crude but accurate assessments of its potential by decision-markers in government and private industry, genetic engineering of crop plants is a world-wide phenomenon, but based essentially in the USA. Selective herbicide resistance to aid better crop management; introduction of plant-derived insecticidal genes (e.g. protease inhibitors); introduction of characteristics associated with resistance to pests, diseases, abiotic and biotic stresses; enhanced quality (e.g. amino acid composition); production of engineered oils, proteins, carbohydrates, enzymes etc. are examples of projects currently underway using several crops or related species.

The diagnosis and quantification of disease organisms are increasingly reliant on biotechnology, as are studies on the relationships between different races, pathotypes and virulence groups. To investigate the mode of action and effectiveness of control agents requires the new technologies, *eg* recombinant antibodies.

Plant breeding is thus one of the leading beneficiaries of genetic engineering. All parts of normal breeding schedules are being revolutionised, from describing the genetic architecture of parental material, overcoming natural breeding barriers and selections, to propagation, prediction of performance and identifying more accurately the added-value properties of the progeny. Speed is of the essence, so is protection of intellectual property.

New plant varieties arising from traditional breeding methods are protected in many countries by plant variety (or breeder's) rights (PVR), without recourse to patent law. Patents are now being granted for the protection of recombinant methods for the production of transgenic plants and their resultant products. Attempts are being made to harmonise patent law and practice internationally. Ethical concerns are expressed about patenting life-forms and claiming ownership. There is freedom to research under both patent and PVR law, but freedom to commercialise is complex, and therefore plant breeders using modern technologies seek protection of both types for law.

Patent protection is unlikely to affect access to existing germplasm and traditional varieties. Genetic resources and diversity are internationally seen as the common heritage of humankind. Biotechnology should and will add to genetic diversity. Counter-arguments centre on the farmer's privilege to save seed to produce subsequent crops without royalty payments to recoup R&D costs, abuse of monopoly provisions, "ordre public" and the public interest, and also the nature of more discovery. Unfortunately for all concerned, a patent of invention does not guarantee a reward for the inventor; simply put, it gives an opportunity for the inventor or patent proprietor to profit from the invention where there is a profitable market for it. Secrecy in some cases is the best commercial protectant in the short term.

Major crops that have been successfully transformed genetically are shown in Table 2.

Table 2. GENETICALLY ENGINEERED MAJOR CROP PLANTS

Species	Transformation method	Field Trials
Banana	Bombardment/*Agrobacterium*	
Barley	Bombardment	Virus resistance
Bean	Bombardment	
Canola	Bombardment/*Agrobacterium*	Herbicide tolerance; pollination control
Cassava	Bombardment/*Agrobacterium*	
Maize	Bombardment/*Agrobacterium*	Insect resistance; her bic ide tol era nce
Cotton	Bombardment/*Agrobacterium*	Insect resistance; herbicide tolerance
Papaya	Bombardment/*Agrobacterium*	Virus resistance
Peanut	Bombardment/*Agrobacterium*	Virus resistance
Poplar	Bombardment/*Agrobacterium*	Herbicide tolerance
Potato	*Agrobacterium*	Insect resistance; virus resistance; herbicide tolerance
Rice	Bombardment/*Agrobacterium*	Herbicide tolerance
Soybean	Bombardment/*Agrobacterium*	Herbicide tolerance
Squash	Bombardment/*Agrobacterium*	Virus resistance
Sugarbeet	*Agrobacterium*	Herbicide tolerance
Sugarcane	Bombardment	
Sunflower	Bombardment	
Tomato	*Agrobacterium*	Delayed ripening; virus resistance

Wheat	Bombardment

From P. Christou. Transformation Technology Trends in Plant Science. 1, 423-431, 1996.

In crops such as soybean, rice and maize, gene-transfer methods have been developed that do not appear to be restricted by cultivar or genotype. Nonetheless, compared with the wide range of good species, few crops have received detailed attention. Moreover, most key traits are multigenic, raising more challenging questions over gene interactions and expression patterns.

For transgenic plants to achieve a small portion of their potential, basic studies will need to expand on the factors (e.g. gene promoters etc.) regulating the expression of introduced genes in different organs and tissues at various phases of growth and differentiation. Industry would be assisted by studies on the biosynthesis and degradation of complex natural polymers such as lignin, cutin, suberin and cellulose, manifestations of cell differentiation, and the cellular components of industrial relevance. Single gene studies will give way to polygenic linked constructions.

Release of GMOs and their products to the environment and for foodstuffs

To a large extent there is relatively little opposition to the use of genetic engineering in most areas of health care, but as the technology is finding application in food production, storage and processing there is widely expressed consumer concern about safety. Some GMOs and their products will continue to be contained strictly within the laboratory environment, others will be monitored closely over a long period to examine their suitability for release into the environment and for consumption. A case-by-case analysis should be carried out in every instance.

Safety is not absolute thus the nub of the argument is one of setting the level of acceptability of risk. By way of definition, hazard is a situation that may lead to harm or loss: risk is the chance in quantitative terms of a defined hazard occurring.

Biologists appreciate that there is natural transfer of genes controlling the formation of toxic principles in plants as well as desirable features. For the most part, species are not static genetically. Through natural selection, for example, resistances to a range of adverse xenobiotics and biotic stresses can be developed.

One huge problem is that the forecasting performance "in the field". We are not knowledgeable about selection pressures operating on organisms, nor about unique recombination events likely to occur. Frankly, it is not feasible for any committee or individual to assess risk for all the possible combinations of genes. Assessment can only come from experimentation and monitoring, employing a battery of scientific disciplines. To date, release experiments have not been problematical. Even naturally occurring mobile DNA elements are limited in their natural hosts, and are not excessively promiscuous. Wilson (1993) cites that an analysis of 393 defined field trials of transgenic plants (25 species) between 1986-1991 (in 21 countries) reveals that 50 involved "virus-resistance" traits. Field releases have shown that coat-protein-mediated protection may not behave as predicted in laboratory and growth-chamber experiments; generally, there is greater susceptibility to virus challenge.

Selectable marker genes, especially relating to the potential impact of antibiotic resistance, raise questions about safety. The potential for uncontrolled gene transfer in the gastro-intestinal tract, soil or by cross-fertilization, or for example herbicide resistance leading to the creation of weeds have received the most attention. What little information is available would not indicate unacceptable risk. Obviously, a great deal of research is still required to quantify risk, if any, and to make recommendations on the use of marker genes. With time, their use will in any case decline, essential markers may need to be inactivated or eliminated prior to release or consumption of the transgenic organism.

Organisational structures to monitor GMO release are already in place in many countries. Much of the real work, though, is labour-intensive, from removal of flowers to stop breeding of transgenics with other plants (especially weeds), surveying experimental sites to eliminate propagules (seeds tubers etc) in the seasons following the experiment, and monitoring gene flow through ecosystems. It is always a good policy for any country to monitor its vegetation anyway. I am deeply suspicious about requirements for "analysis of benefit" prior to permission being given for the release and use of GMOs. Just who sets the criteria of benefit and performs the analysis? Central planning can be debilitating when prudency and responsible care are the objectives.

Public Attitudes

Voters comprise heterogeneous groups who determine the political, industrial and economic climate of democratic countries. Their taxes and those of private companies support R&D programmes in the public sector. They are also consumers who should be free to exercise choice. Scientists should be providing them with factual basis for reaching informed decisions.

In contrast to healthcare, applications of modern biotechnology to food and the environment are greatly influenced by the level of education, perceived social and ethical issues, as well as reaction, frequent irrational, responses towards non-medical sciences.

There are also objections at a secondary level to the role of multinational companies carrying out genetic engineering and failing to take adequately into account the impact of their activities on the less-developed world, playing one economy off against another, or riding roughshod over the need to label products. Although not necessarily associated with religious organisations, there is also the oft-cited "unnatural" or "ungodliness" aspect of science replacing natural functions, generating chimaeric organisations, or fiddling with life for profit.

Ignorance of science and technology, as much as ignorance of business, leads to fear, anxiety and reluctance to fund research and development projects. Pressure groups of all kinds are formed. It seems that the public derive most of their limited understanding of science through the arts-dominated media, especially television, where all too often artistic license embellishes scientific observation with imaginative doom-laden claptrap. This must cause the scientific and advanced industrial communities a measure of introspection. Healthy scientific scepticism, questioning, sharp debate, experimentation and wide-ranging open-mind interpretations and conclusions are the stuff of science. So is presentation. There can be no room for indolence nor ineptitude. Scientists, like the public, cover a spectrum of views and attitudes and are difficult to organise except into cliques. The public must realise that it is entirely technology-dependent. Scientists in turn accept justifiable control as much as the financial backing. I am worried that the foucault pendulum is swinging towards harsher controls which cannot be sustained in the longer term even though it is unfashionable to argue against any moves restraining science. Sometimes, pressure groups have vested political interests or social engineering at heart. Nonetheless, a balance-point must be reached, taking into account illogical fears, damage to the environment, healthcare, and the need for science. The need for genetic engineering is irrefutable. It is how we do it that we must get right.

At this juncture, there is a view that only by being aware of obvious benefits to the consumer (e.g. increased safety because of reduced natural toxins, lower costs, post- and disease-free produce, better and more consistent quality etc.) or to the environment (e.g. reduced pesticide inputs, bioremediation etc.) will there be general acceptance to genetic engineering. Fewer problems are experienced with plant-plant than with plant-microbe transgenetics; plant-animal and animal-animal combinations, most notably where "human" genes are concerned can provide virulent public and pressure group reactions. The greatest level of acceptance seems to favour transgenic plants used for non-food purposes. Meanwhile, there will be a plethora of legislative barriers. In the medium to long term, however, the imperative to acquire food will create the demand for the benefits of plant biotechnology.

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