STATUS OF RESEARCH AND APPLICATION OF CROP BIOTECHNOLOGIES IN DEVELOPING COUNTRIES

Preliminary assessment

ISBN 92-5-105290-5

STATUS OF RESEARCH AND APPLICATION OF CROP BIOTECHNOLOGIES IN DEVELOPING COUNTRIES

Preliminary assessment

Z. Dhlamini
Associate Professional Officer (Biotechnology)
FAO Research and Technology Development Service

C. Spillane
FAO Consultant
Science Foundation Ireland Investigator
Department of Biochemistry, University College Cork, Ireland

J.P. Moss
FAO Consultant
Former Director of the Cellular and Molecular Biology Division
International Crops Research Institute for the Semi-Arid Tropics, Hyderabad, India

J. Ruane
Agricultural Officer (Biotechnology)
FAO Working Group on Biotechnology

N. Urquia
Seed and Plant Genetic Resources Officer
FAO Seed and Plant Genetic Resources Service

A. Sonnino
Senior Agricultural Research Officer
FAO Research and Technology Development Service

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2005

Contents

Abbreviations

AFLP	Amplified Fragment-Length Polymorphism
ASPV	Apple Stem Pitting Virus
BNF	Biological Nitrogen Fixation
Bt	*Bacillus thuringiensis*
BTV	Bunchy Top Virus
BYDV	Barley Yellow Dwarf Virus
CBD	Convention on Biological Diversity
CGIAR	Consultative Group on International Agricultural Research
CIMMYT	Centro Internacional de Mejoramiento Maiz y Trigo
CMV	Cucumber Mosaic Virus
COAG	FAO Committee on Agriculture
CpTI	Cowpea Trypsin Inhibitor
CVbMV	Chilli vein-banding mottle virus
DNA	Deoxyribonucleic Acid
ELISA	Enzyme Linked Immunosorbent Assay
FAO	Food and Agriculture Organization of the United Nations
FAO-BioDeC	FAO Biotechnology In Developing Countries Database
FAOSTAT	Corporate Database for Substantive Statistical Data
GM	Genetically Modified
GMO	Genetically Modified Organism
IDWGB	Interdepartmental Working Group on Biotechnology
IPM	Integrated Pest Management
ISNAR	International Service for National Agricultural Research
MAS	Marker-assisted Selection
MIRCEN	Microbiological Resources Centre of UNESCO
MSV	Maize Streak Virus
NARS	National Agriculture Research System
NPV	Nucleopolyhedrosis Virus
PAIA	Priority Area for Interdisciplinary Action
PAMV	Potato Aucuba Mosaic Virus
PCR	Polymerase Chain Reaction
PEM	Protein-Energy Malnutrition
PepLCV	Pepper Leaf Curl Virus
PLRV	Potato Leaf Roll Virus
PPV	Plum Pox Virus
PRSV	Papaya Ringspot Virus
PVA	Potato Virus A
PVM	Potato Virus M
PVX	Potato Virus X

PVY	Potato Virus Y
PVYV	Pear Vein Yellow Virus
QPM	Quality Protein Maize
QTL	Quantitative Trait Locus
R&D	Research and Development
RAPD	Random Amplified Polymorphic DNA
RDV	Rice Dwarf Virus
RFLP	Restriction Fragment Length Polymorphism
SCMV	Sugar cane Mosaic Virus
SMV2	Soybean Mosaic Virus 2
SNP	Single Nucleotide Polymorphism
SPFMV	Sweet Potato Feathery Mottle Virus
TMV	Tobacco Mosaic Virus
TSWV	Tomato Spotted Wilt Virus
TYLCV	Tomato Yellow Leaf Curl Virus
UNESCO	United Nations Educational, Scientific and Cultural Organization
VAD	Vitamin A Deficiency
WYMV	Wheat Yellow Mosaic Virus
ZaMV	Zantedeschia Mosaic Virus
ZYMV	Zucchini Yellow Mosaic Potyvirus

Executive summary

FAO and its Governing Bodies recognize the role biotechnology can play in augmenting agricultural production when properly integrated with other technologies. Member countries look to FAO's assistance in strengthening their institutions through provision of technical, legal and policy advice as well as promotion of information exchange. Information on biotechnology activities in developing countries is scarce and this has prompted FAO to develop an inventory of plant biotechnology products and techniques in use or in the pipeline in developing countries. The inventory has been compiled and organized into a searchable online database called the FAO Biotechnology In Developing Countries Database (FAO-BioDeC). This document summarizes and analyses the information contained in the database as of 31 August 2004.

Individual country information in the database is organized in two broad categories: genetically modified crops and other biotechnologies. The status of application is divided into three classes: research phase, field trials and commercialization (in the case of genetically modified organisms (GMOs) or routine utilization (in the case of other biotechnologies).

GMOs are classified within the database as having genes conferring resistance to pests (*Lepidoptera*, *Coleoptera*, nematodes), pathogens (viruses, bacteria and fungi), herbicides (gluphosinate, glyphosate, phosphinotricin), abiotic stresses (frost, salt, heat and drought) or modified for improved quality traits (vitamin content, oil composition, protein quality and altered growth/development). GMO activities (479 records, Table 12) are ongoing in many countries but unevenly distributed, with Latin America and Asia recording 85 percent of all recorded GMO activities in the developing world (45 percent and 40 percent, respectively). GMO activities aimed at pathogen resistant cultivars form 35 percent of the total activities, followed by pest resistance at 20 percent, quality traits and herbicide resistance each at 16 percent. Most of the commercialized GMOs were acquired from developed countries and are mainly herbicide and Bt resistant cotton, maize and soybean cultivars. From the number of field trials (40 percent of all GMO activities) it can be postulated that in the near future the developing country markets will have new GM crops such as virus resistant papaya, sweet potato and cassava; rice tolerant to abiotic stress (salinity and drought), and even high lysine maize and soybeans with improved oil composition. However, a lot of biosafety capacity building is needed to enable many countries in Africa, Eastern Europe and the Near East to benefit from this technology.

The use of other biotechnologies, such as micropropagation, molecular markers, diagnostics and microbial techniques, in developing countries is much more prevalent (1 351) activities recorded: Table 14) and the distribution of the activities seems not as skewed between regions as in the case of GMOs. For example, plant propagation techniques are the most used (49 percent) of all biotechnologies and regional proportions are as follows: Latin America, 30 percent; Asia, 28 percent; Africa, 20 percent; Eastern Europe, 18 percent; and the Near East, 4 percent. Generally, there may be under-reporting of some technologies that are considered too routine. Future information gathering for the FAO-BioDeC should strive to highlight all these biotechnology applications. Many of these technologies are being used on a commercial scale but only a few studies have been carried out to assess their socio-economic impacts. This is an area that needs urgent attention as it is likely to help guide research and technology policies towards wider and efficient utilization of all the biotechnologies.

Even though the database is not complete at present, it does give a clear picture of developing country and regional competencies in biotechnology and can be used to identify potential partners for joint programmes. A network of country correspondents has been put into place for the regular updating of the database. In the near future the FAO-BioDeC will be expanded to cover the forestry, animal and fisheries sectors.

1. Introduction

The FAO Committee on Agriculture (COAG), whose main task is to review and provide advice on FAO's programme of work in food and agriculture, including on selected international development issues, stressed in 1999 that biotechnology, when coupled with other technologies, offers considerable potential and opportunity for new solutions to some of the old problems hindering sustainable rural development and achievement of food security, but also notes that it is an area where there is a growing gap between developing and developed countries. To take advantage of the biotechnology promise, many FAO member countries need assistance in strengthening their overall capabilities in research and development, and at the policy and regulation level.

The member countries have in particular recommended that FAO provide, on request, policy advice for biotechnology issues related to food and agriculture; promote information exchange, and provide technical and legal assistance and advice to its members. In addition, member countries recommended that FAO develop a strategic approach with emphasis on the coordination of a cross-sectorial programme on biotechnology.

Priority Areas for Interdisciplinary Action (PAIAs) have been identified within FAO's strategic framework for 2000-2015. An Interdepartmental Working Group on Biotechnology (IDWGB) was established in 1999 to guide and coordinate FAO's strategic approach under the new PAIA on biotechnology.

The IDWGB identified the development of an inventory of plant biotechnological products and techniques in use and in the pipeline in developing and transition countries as a means of contributing to the information exchange needs of its member countries. It may help them to identify needs and gaps in agricultural biotechnology research, becoming a decision-making tool for policy-makers to establish or revise national priorities. In addition, such an inventory offers countries the opportunity to give a closer look at programmes in neighbouring countries and identify potential partners for joint programmes. Finally, examination of all the data makes it possible to carry out global analyses of biotechnology applications in developing countries and in countries with transition economies and to make comparisons between regions.

The inventory has now been compiled, and the information has been organized in a searchable database called the FAO-BioDeC (FAO Biotechnology in Developing Countries). It was launched in April 2003 and is available on the FAO Biotechnology web site at: http://www.fao.org/biotech/inventory_admin/dep/default.asp. The database is still incomplete at this first stage. Verification and regular updating of information in the database is being carried out through a network of national correspondents.

This document presents a preliminary assessment of the status of application of biotechnology in developing countries based on the review of the information already present in the FAO-BioDeC as of 31 August 2004. The main purpose of this document is to present some of the types of data and analyses that can be gleaned from its current content and structure. As the database is still far from being complete, the overview presented is quite preliminary. Nevertheless, it should allow a meaningful analysis of the status of applications of crop biotechnology in developing countries to be carried out.

In particular, it should be noted that the current content of the inventory is a preliminary representation of the extent of research and development in plant biotechnology research and development in many countries. Where data is currently absent in the FAO-BioDeC, it is not possible to conclude for that country that a particular type of research is absent, as information may simply be lacking and activities unreported. More reliable interpretation of the data will be obtained from looking at what data are definitively incorporated in the database (i.e. to focus on the positive data rather than inferred negative data). Furthermore, where research programmes are involved, this analysis does not differentiate between ongoing and terminated projects as this information was not readily available for this first edition of the FAO-BioDeC. However, the database allows for the inclusion of project start and end dates, and this will be implemented for future data updates. This document and the information it contains should therefore be used as the first step of a process to develop a more structured and streamlined inventory which will eventually allow countries to make up-to-date analyses of existing activities in biotechnology application.

2. Scope and methodology of the FAO-BioDeC

For the purpose of this inventory, biotechnology has been defined as "any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use" (CBD, 1992). This definition can be interpreted in a wide sense to cover not only recombinant DNA technologies such as genetic engineering which result in transgenic organisms, but also to include other forms of non-transgenic biotechnology R&D such as genomics, marker-assisted breeding, micropropagation and agricultural diagnostics. For definitions of these and other technical terms used throughout the document, see FAO (2001).

At this stage, the FAO-BioDeC includes about 2 000 entries from 71 developing countries, including countries with economies in transition (Appendix 1). The database in this initial phase is limited to research, testing and commercialization of specific crop technologies and products in developing countries. It also has a section on country profiles, which summarize individual country biotechnology-related policies, regulations and activities. The database will be later expanded to include the animal, fisheries and forestry sectors as well as information on the biotechnology regulatory status in the member countries.

No quantitative information is available with regard to the human capacity or funding involved. It does not cover activities carried out in developed countries even if they are meant for subsequent use or adoption in developing countries, nor does it cover research being carried out at international research centres, such as those that are part of the Consultative Group on International Agricultural Research (CGIAR), located in developing countries.

To compile the FAO-BioDeC a number of data sources have been consulted. In particular, information on plant biotechnology products and techniques gathered from a survey undertaken in Latin America by the International Service for National Agricultural Research (ISNAR) and from country biotechnology status assessment reports undertaken by FAO in South East Asia, Africa, and transition countries in Eastern Europe. Some information was obtained from country reports and published literature.

The initial biotechnology application data obtained has been classified on a country/regional/continental basis, by species, trait analysed or technique used, and by whether the application is in the research phase, field testing phase or already commercially released (or routinely utilized in the case of non-GM technologies).

The data currently entered in the FAO-BioDeC has been subjected to some preliminary analysis outlined in the text in different sections of this document.

3. Analysis of the FAO-BioDeC data on non-GM biotechnologies

A number of non-GM biotechnologies are currently being used in developing countries in the agricultural sector. These techniques have been grouped in four main clusters: microbial, cell biology, molecular marker and diagnostic, each of them divided into subgroupings for specific techniques. Subgroupings under "other" have been included to cover unspecified activities under each cluster. The information gathered is analysed by region, species and technique, and summary tables have been included to facilitate the analysis. In the tables, research on one trait or technique in one crop in one country is counted as one initiative.

3.1 MICROBIAL PRODUCTS FOR AGRICULTURE

Microbiological techniques are central to the production, harvesting and use of many agricultural products. The use of microbial techniques includes the design or delivery of microorganisms for the control of pests (biocontrol agents or biopesticides), as fertilizers (biofertilizers) and for fermentation and food processing techniques. From data in the FAO-BioDeC (Table 1), it seems that research towards the scientific development of biocontrol agents (biopesticides), biofertilizers and fermentation and food processing microbial techniques, is at the early stages in Africa and Asia, (with the exception of China and India), while Latin American countries are already using advanced techniques on a more routine basis and some of the results obtained are already being tested. It should be borne in mind that many production and post-production processes already in use by farmers have a microbiological basis and that the extent of use of microbiological techniques in agriculture is grossly under reported by focusing only on the use of microbiological techniques which emanated from 'modern' laboratories, rather than also on the use of microbiological techniques developed as indigenous or local knowledge of farmers and consumers.

3.1.1 Microbial agents for the biocontrol of pests

Although considerable use of classical pesticides persists, in some countries there is a trend towards using newer pesticides that are more selective, less toxic to humans and the environment, and require less application per hectare to be effective. A small but growing percentage of these are biopesticides, including microbial pesticides like *Bacillus thuringiensis* (Bt), and biocontrol agents such as pheromones, growth regulators and hormones. In addition, there is growing acceptance of use of such alternative pest control agents in various forms of Integrated Pest Management (IPM). Biocontrol agents, or biopesticides, range

TABLE 1

Number of initiatives to develop and use microbial techniques

Technique	Region																													
	Africa					Asia					Eastern Europe					Latin America					Near East					Total				
	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N
Biocontrol	-	-	11	-	7	-	-	3	-	3	-	2	6	-	2	-	9	2	-	2	-	-	2	-	2	-	11	24	-	16
Biofertilizers	1	-	7	6	10	-	-	10	3	6	-	4	1	-	4	-	3	3	-	3	-	-	1	-	1	1	7	22	9	24
Fermentation	-	-	4	-	5	-	-	7	-	2	10	1	1	-	4	1	3	7	-	5	-	-	-	-	-	11	4	19	-	16
Other	-	-	-	-		-	-	-	3	2	-	3	3	-	2	-	2	5	-	4	-	-	-	-	-	-	5	8	3	9
Total	1	-	22	6	12	-	-	20	6	7	10	10	11	-	5	1	17	17	-	6	-	-	3	-	2	12	27	73	12	32

C: technology used on a routine basis and products available on the market; T: results being tested; E: number of activities at experimental level (including laboratory or glasshouse activities); U: activities in unknown phase; N: number of countries involved. (Totals of this column have been calculated taking into account that sometimes more than one activity is being carried out by the same country, although that country will only be counted once).

from the classic *Bacillus thuringiensis (*Bt*)* to *Trichoderma*, *Verticillium*, *Bauveria*, *Bacillus subtilis* to plant extracts, entomophagic nematodes or entomopathogenic viruses, such as nucleopolyhedrosis virus (NPV).

Table 1 shows that reported research on biological control agents is only at the laboratory phase in Africa, with emphasis on application to cowpea in Ghana and Kenya, sorghum in Ethiopia, Kenya and Zimbabwe, banana in South Africa, Uganda and Zimbabwe, cassava in Malawi and sugar cane in South Africa. In Eastern Europe, both Georgia and the Republic of Moldova have trials underway on use of *Trichoderma* spp as a biocontrol agent. Research on *Metarhizium anisopliae, Entomophora* spp. is undertaken in Georgia and on pathogenic bacteria, fungi and viruses in the Republic of Moldova . In Asia, use of *Steinernema thailandensis* is established and laboratory research is underway on Bt and NPV for use as biopesticides in Thailand. In Latin America, Guatemala is testing botanical extracts and *Bacillus subtilis* on melons and tomato, *B. subtilis* on pea, entomopathogenic fungi on sugar cane and pasture, and Bt/NPV on ornamental, horticultural and other crops. Chile is researching biocontrol of scab in apple. In the Near East, Egypt and Morocco are researching biocontrol of *Fusarium* in date palm.

3.1.2 Biofertilizers

Biological nitrogen fixation (BNF) refers to the process of microorganisms fixing atmospheric nitrogen, mostly within subsoil plant nodules, and making it available for assimilation by plants. Nitrogen availability is a key limiting factor in crop production. *Rhizobia* are the most studied and important genera of nitrogen fixing bacteria, but also a number of endophytic bacteria are now known as nitrogen fixing organisms. Use of biofertilizers, such as *Rhizobium* or other symbiotic and non-symbiotic species for atmospheric nitrogen fixation represents a more environmentally-friendly alternative to chemically generated fertilizers. Other microorganisms, such as *Mycorrhiza*, are active in establishing symbiosis with cultivated plants and forest trees, and facilitate phosphorus uptake. Inoculation with these fungi has proven to be an efficient way to substitute or complement phosphorus-based chemical fertilization.

The only reported research on biofertilizers in the Near East is research into *Rhizobium* in food legumes in Morocco. In Latin America, techniques for increasing nitrogen fixation in soybean, bean and cowpea are being tested in Venezuela, and researched in rice in Brazil, where arbuscular mycorrhiza are also being tested in native trees. Argentina has started nitrogen-fixation research on unspecified microorganisms. In Asia, India is researching *Rhizobium* with high capacity for nitrogen fixation, and China is studying *Rhizobium* in rice and maize. Indonesia is investigating vascular arbuscular mycorrhiza, the Philippines mycorrhiza and *Rhizobium* in forest species, and Viet Nam is experimenting with *Rhizobium* strains for the Mekong delta soils.

In Africa, research into biofertilizers for sorghum is ongoing in Ethiopia, Kenya and Zimbabwe, for cowpea in Cameroon, for groundnut and bambara groundnut in Madagascar, and for rice in Rwanda, with unspecified work in Burkina Faso, Cote d'Ivoire, the Democratic Republic of the Congo, Kenya, Rwanda and Senegal. The UNESCO Microbiological Resources Centre (MIRCEN) project at the University of Nairobi in Kenya has, since 1981, developed a *Rhizobium* inoculant known as *BIOFIX*, currently the main inoculant available on the local market. In Eastern Europe, Armenia and the Republic of Moldova are testing *Azotobacter* and *Rhizobium*.

3.1.3 Fermentation technology and food processing

Biotechnology in the food processing sector targets the selection and improvement of microorganisms with the objectives of improving process control, yields and efficiency as well as the quality, safety and consistency of bioprocessed products (FAO, 2004a). These microorganisms are used in fermentation; the process of bioconversion of organic substances by microorganisms and/or enzymes (complex proteins) of microbial, plant or animal origin. Fermentation is one of the oldest forms of food processing which is applied globally. In developing countries, fermented foods are produced primarily at the household and village level, where they find wide consumer acceptance. Food fermentations contribute substantially to food safety and food security, particularly in the rural areas of many developing countries.

The extent of application of biotechnologies such as fermentation technology and various food processing techniques is immense and difficult to monitor using a database such as the FAO-BioDeC. Nevertheless, it indicates that fermentation technology and food processing is quite commercialized in Latin America for sorghum in Brazil, where food enzymes are also being tested in several species of grains and vegetables, and researched in sugar cane. In Eastern Europe, *Lactobacillus*, *Acetobacter* and *Saccharomyces* are reported as being used commercially in Armenia, Georgia and the Republic of Moldova , where *Bacillus subtilis*, is also being used. *Actinomycetes* are being tested in Azerbaijan, and *Bacillus vulgaris* researched in Armenia. In Africa, research phase initiatives are underway in the fermentation of banana in Kenya and Zimbabwe, cowpea in Cameroon, cassava in Nigeria, with unspecified research in Burkina Faso. In Asia, Indonesia is researching lactic acid bacteria, dextranase, xanthan gum production and soybean fermentation. China and Indonesia are reported to be working on the use of the phytase enzyme in improving animal feed.

3.1.4 Environmental biotechnology

Environmental biotechnology can be defined as the development, use and regulation of biological systems for remediation of contaminated environments (land, air, water), and for environment-friendly processes (green manufacturing technologies and sustainable development). The FAO-BioDeC reveals few environmental biotechnology initiatives of relevance to food and agriculture underway in the countries surveyed. However, it is reported that microbiologial techniques for environmental management are being investigated in Indonesia, for biological waste and water treatment and bioconversion of solasodine, and in Thailand for biodegradable plastics and waste treatments. In Eastern Europe, Azerbaijan is testing *Basidiomycetes, Deyteromycetes,* and *Fungi imperfecti* and Georgia is researching *Mycobacteria, Halobacterium halovium,* and *Aspergillus terreus*. In Latin America, Chile is testing *Thermomyces lanuginosus* for cellulase production, and bacterial biofilm for bioremediation.

3.2 APPLIED PLANT CELL BIOLOGY TECHNIQUES

3.2.1 Micropropagation

Micropropagation is the use of tissue culture methods to propagate plants. Using micropropagation, millions of new (clonal) plants can potentially be derived from a single plant. Micropropagation encompasses a range of tissue culture techniques for propagation of plant species. In essence, tissue from a plant (explant) is isolated to create a sterile culture of that species *in vitro*. Once a culture is stabilized and growing well *in vitro*, multiplication of the tissue or regeneration of entire plants can be carried out. Shoots (tips, nodes or internodes) and leaf pieces are commonly used but cultures can be generated from many different tissues. Juvenile tissues generally respond best. This method of cultivation of plant material is used for:

- rapid, large-scale, year round production of desired horticultural varieties (e.g. many of the popular miniature rose varieties are produced this way);
- propagation of plant species that are difficult to grow from seed;
- production of genetically uniform plant material ("clones");
- development of plant culture systems that can be used for genetic transformation, e.g. to introduce disease resistance; and
- production of disease-free plant material (e.g. potato microtubers).

The benefits of plant tissue culture propagation include potentially unlimited multiplication of superior plant lines or elite individuals, avoidance of contamination with pathogens, production of true-to-type multiplication material of desirable plant lines suited for indefinite storage through cryopreservation, or for long-term maintenance of propagule inventories. In comparison to other plant propagation techniques, the major limitation of the application of this technology is the need for technically skilled labourers and some essential equipment. It is therefore commercially applied to high value added crops, which are worth the necessary investment.

Micropropagation is now a 'mature' plant biotechnology and is among the most widely used plant biotechnologies, reportedly being applied in 21 countries in Africa, ten in Asia, nine in Eastern Europe, nine in Latin America and eight in the Near East (Tables 2 and 3).

The success of micropropagation may be explained by its relatively low costs and generally positive effects on productivity (especially of clonally propagated root and tuber crops). Micropropagation has become an irreplaceable tool for many clonally propagated species for the production of pathogen-free plantlets (among such clonally propagated crops are 10 of the 30 most cultivated crops worldwide). Emphasis on the development of cost-effective micropropagation techniques is expected to increase even further.

TABLE 2
Number of tissue culture initiatives

Technique	Region																													
	Africa					Asia					Eastern Europe					Latin America					Near East					Total				
	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N
Micropropagation	15	1	64	-	21	17	8	57	51	10	1	15	38	-	9	4	62	25	2	8	7	-	5	-	8	44	86	189	53	57
Anther culture	-	-	4	-	2	-	1	10	9	3	-	-	5	-	3	3	11	5	-	6	2	1	6	-	4	5	13	30	9	18
Embryo rescue	-	-	1	1	2	-	-	2	-	1	-	-	3	-	3	6	14	4	-	6	-	-	3	-	3	6	14	13	1	15
Protoplast fusion and culture	-	-	2	-	1	-	-	8	2	2	-	-	10	-	4	-	-	-	-	-	-	-	1	-	1	-	-	21	2	8
In vitro techniques	-	-	22	1	7	-	-	4	-	2	-	6	11	-	5	-	29	9	-	6	-	-	1	-	1	-	35	47	1	21
Other	-	-	24	-	12	1	-	11	2	1	-	-	29	2	5	3	10	9	-	4	-	-	3	-	3	4	10	76	4	25
Total	15	1	117	2	21	18	9	92	64	10	1	21	96	2	9	16	126	52	2	9	9	1	19	-	8	59	158	376	70	57

C: technology used on a routine basis and products available on the market; T: results being tested; E: number of activities at experimental level (including laboratory or glasshouse activities); U: activities in unknown phase; N: number of countries involved. (Totals of this column have been calculated taking into account that sometimes more than one activity is being carried out by the same country, although that country will only be counted once).

The FAO-BioDeC indicated that micropropagation is routinely being used, with many commercial products available on the market. In Latin America, micropropagation is used for blueberry, raspberry, sugar cane and potato in Argentina, and sugar cane, blackberry, strawberry, apple, potato, banana, cassava, pineapple, violet, fruits, cereals and ornamentals in Brazil. In Asia, Bangladesh has micropropagated plants of banana, orchid, chrysanthemum, potato, jackfruit, pineapple and unspecified timber trees; Nepal has micropropagated potato, orchids and *Miscanthus* spp. In Eastern Europe, Yugoslavia has micropropagated potato, while in the Near East, date palm is being commercially propagated in the Islamic Republic of Iran, Kuwait, Morocco, Tunisia and the United Arab Emirates. Tunisia also has available micropropagated *Prunus* rootstocks, almond, citrus, grape, olive and pistachio. The Islamic Republic of Iran, Jordan and the Syrian Arab Republic have potatoes, and in addition banana is available in the Islamic Republic of Iran. In Africa, micropropagated banana is promoted in Cameroon, Gabon, Kenya and Uganda. In addition, plantain and cassava are promoted in Gabon, and yam, potato and sweet potato in Uganda.

A wide range of micropropagated ornamentals, trees and food crops, with emphasis on root and fruit crops, are being tested for commercial production, or are in the preliminary research phase in all regions.

3.2.2 Anther and pollen culture

Anther culture involves the aseptic culture of immature anthers to generate fertile haploid plants from microspores. The production of haploid plants through anther culture is widely used for breeding purposes, as an alternative to the numerous cycles of inbreeding or backcrossing usually needed to obtain pure lines in conventional breeding. The success achieved with anther culture has led to the development of microspore culture. This involves the isolation of the microspores from the anthers, culturing them in specialized media and subsequent regeneration of fertile homozygous plants. Furthermore, isolated microspores are very attractive for protoplast isolation and applications aiming at transformation as they are unicellular and transgenic homozygous plants could be provided in a comparatively short time.

In vitro anther culture is now routinely used for improving some vegetable crops such as asparagus, sweet pepper, eggplant, watermelon and *Brassica* vegetables. In addition, anther culture is being increasingly used in cereal crop improvement both as a source of haploids and new genetic variation. Isolated microspore culture has been successfully carried out with some *Brassica* vegetables such as cabbage, broccoli and Chinese cabbage-petsai and pakchoi. Most genotypes respond better to isolated microspore culture and embryo yield is generally higher than with anther culture. Therefore, isolated microspore culture has been preferred as a breeding tool and as an experimental system for various genetic manipulations. A Chinese cabbage breeding programme using this technique is underway in the Beijing Vegetable Research Center.

In Asia, three countries are reportedly using anther culture (Table 2). In China, for example anther culture is being applied in different species such as wheat, rice,

TABLE 3
Some examples of countries using plant propagation techniques for different crops at the commercial level

Crop or species	Countries
Micropropagation	
Potato	Bangladesh, Islamic Republic of Iran, Jordan, Nepal, Syrian Arab Republic, Uganda.
Sweet potato	Uganda
Plantain, cassava	Gabon
Banana	Bangladesh, Cameroon, Gabon, Islamic Republic of Iran, Kenya, Myanmar, Uganda
Date palm	Islamic Republic of Iran, Kuwait, Morocco, Tunisia, United Arab Emirates
Jackfruit	Bangladesh
Pineapple	Bangladesh, Myanmar
Citrus, almond, *prunus* rootstocks, grape, olive, pistachio	Tunisia
Anther culture	
Bread wheat	Morocco
Durum wheat	Tunisia
Fruits, cereals and ornamentals	Brazil
Embryo rescue	
Banana, citrus, papaya, fruits, cereals and ornamentals	Brazil
Germplasm conservation	
Cassava, violet	Brazil
Other propagation techniques	
Kakrol	Bangladesh

maize, rubber, hot pepper, poplar and sugar beet. Bangladesh is conducting trials on anther culture derived rice with salt tolerance and anther culture research on mulberry, maize, jute barley and tea, and Nepal has research on rice and wheat. In the Near East, anther culture research emphasis is on cereals. An anther culture generated durum wheat variety has reached the commercial phase in Tunisia, and anther culture techniques are being researched in Morocco, where an anther cultured bread wheat is in commercial use. Anther culture techniques are being tested in the Sudan, and applied to barley in the Islamic Republic of Iran, Iraq, Morocco and the Syrian Arab Republic. Wheat is also being researched regarding anther culture in Eastern Europe in the former Yugoslav Republic of Macedonia and Serbia and Montenegro.

In Latin America, varieties obtained through anther culture of unspecified fruits, cereals and ornamentals have reached the commercial stage in Brazil. Advanced testing of anther culture derived varieties of 'many plants' is reported in Costa Rica, and in Venezuela cocoa, rice, sugar cane, papaya, mango and bamboo are also being tested. Anther culture derived rice varieties are under advanced testing also in Argentina, and in Brazil, where this technique is specifically used in breeding for blast resistance. In Chile, wheat, barley and rice, are in the research phase. Other anther culture research is carried out on maize and onion in Argentina, wheat in Ecuador and asparagus in Peru. In Africa, anther culture research has started on banana in Cameroon and on sorghum and rice in Mali.

3.2.3 Embryo rescue

In embryo rescue/culture, the embryo is removed before seed abortion occurs and is grown outside the parent plant to produce a new plant to enable crosses to be made between species which would not normally be sexually compatible. *In vitro* embryo rescue techniques are therefore often used to rescue plant embryos from aborting progeny seeds that result when two distantly related plants (e.g. two species) are crossed together. Such 'wide crosses' are often desirable to transfer genetic traits from the secondary and tertiary genepools (i.e. crop wild relatives) to the cultivated primary genepools of crop plants. This technique is used in breeding of many crop species and allowed synthesis of triticale, a new hybrid species resulting from the cross between rye and wheat.

In the Near East, embryo rescue techniques are being developed in Algeria, Morocco and the Sudan. In Eastern Europe, embryo culture research is underway on sweet and sour cherry in the former Yugoslav Republic of Macedonia, sunflower in Yugoslavia, and maize in the Republic of Moldova. Only in Latin America has extensive use been made of the embryo culture technique, where it has given rise to commercially viable new varieties in banana, citrus, papaya, fruits, cereals and ornamentals in Brazil. New embryo rescue-derived varieties are tested in maize, *Celtis tala, Erthytrina crista galli, Acacia caven* and *Elymus spp*. in Argentina, in grape in Chile, in orchids in Costa Rica and in rice, sugar cane, papaya, *Solanum nigrum*, Yantén, *Spathiphyllum* sp., *Aster* sp., and gloxinia in Venezuela. Research is at an early stage in Africa, on yam in Nigeria and unspecified work is being carried out in Cameroon, and also in Asia, where the only embryo culture report is of work on rice and orchid in Bangladesh.

3.2.4 In vitro regeneration and somaclonal variation

Plant regeneration from cell cultures is central to the application of gene transfer techniques such as biolistics and *Agrobacterium*-mediated transformation. Not all plants are readily amenable to *in vitro* regeneration and there is thus a need to continuously develop regeneration protocols for the recalcitrant species if they are to benefit from genetic modification technologies. In vitro regeneration usually results in high genetic and phenotypic variability in individuals derived from cultures, which is called somatic variation. Somatic variation can be beneficial in crop improvement especially on traits for which somaclonal mutants can be enriched during *in vitro* culture, including resistance to disease pathotoxins, herbicides and tolerance to environmental or chemical stress, as well as for increased production of secondary metabolites.

Advanced *in vitro* regeneration work (protocol testing) is reported in *Acacia caven*, *Erythrina crista galli*, potato, sweet potato, cassava and garlic in Argentina, in blueberry in Chile, in cassava, aroids, *Musa* sp., *Coffea* sp., banana and plantains in Costa Rica, in *Ullucus tuberosus*, *Oxalis tuberosa*, *Tropaeolum tuberosum*, *Arracacia xanthorrhiza*, *Mirabilis expansa*, *Canna edulis*, and manihot in Ecuador and in tropical fruits, roots and tubers, cassava, potato, *Musa*, *Solanum nigrum*, Yantén, *Spathiphyllum* sp., *Aster* sp., and gloxinia in Venezuela. Research is in the laboratory stage (protocol development) on *Parkinsonia aculeate*, *Elymus* sp, and *Ilex paraguariensis* in Argentina, red clover and garlic in Chile, and on *Mycosphaerella fijiensis*, *Rosellinia spp.* and selected plant species in Costa Rica. In Asia, the only reported initiative is research on somaclonal variation in mulberry in Bangladesh.

3.2.5 In vitro germplasm conservation and cryopreservation

Biotechnology can play an important role in the conservation of germplasm of many crop species, whether the germplasm is maintained as vegetative or seed propagules. *In vitro* conservation protects germplasm from possible contamination with pathogenic agents and preserves the genetic identity of the stored material. Germplasm regeneration techniques (*in vitro* or *in vivo*) coupled to cryopreservation protocols ensure the long-term, safe storage of much of the world's germplasm, even if this technique is well established only for a number of plant species. The FAO-BioDeC include information on the use of *in vitro* conservation and cryopreservation. In this regard, the only work reported in Asia is experiments in Viet Nam on sugar cane and in Bangladesh on orchid, bamboo and hybrid *Acacia*. Similarly in Africa, reported work is only in the experimental phase, concentrating on root crops, cassava in Cameroon, Ghana and Nigeria, yams in Cameroon, Malawi and Nigeria, sweet potato and potato in Kenya, also on banana in Ghana, Malawi, Nigeria and Uganda, with unspecified activities in Cote d'Ivoire. In Latin America, use in cassava and violet is reported in Brazil, where experiments are also underway on sugar cane. Chile has developed cryopreservation of *Fragaria chiloensis* at the laboratory stage. In the Near East, only Egypt has any activity, in the laboratory, on potato conservation. In Eastern Europe, the former Yugoslav Republic of Macedonia is conducting trials on techniques for *in vitro* conservation of grape, apple, strawberry and cherry, and Yugoslavia for sunflower and potato. Experimental work is ongoing for potato in Albania and Bosnia and Herzegovina, also on *Populus, Genthiana sp.,* and 30 wild species in Bosnia and Herzegovina and on *Salvia hydrangea*, *Bryonia alba*, *Atropa belladonna*, *Rubia tinctorum*, *Hypericum perforatum*, and *Melissa officinalis* in Armenia and grapevine in Azerbaijan.

3.3 MOLECULAR MARKER TECHNIQUES

Molecular marker techniques (employing RFLP, RAPD, microsatellites, AFLP, SNP and other kinds of marker systems) represent a rapidly evolving suite of powerful research tools for the characterization and management of genetic polymorphism (variation and diversity) in plant breeding and germplasm characterization programmes. Where they are available and cost-effective, molecular markers can have a wide number of applications in plant breeding, the most commonly considered being marker-assisted selection (MAS). The FAO-BioDeC suggests that the earliest generation forms of DNA-based molecular markers (RAPD, RFLP) are more widely used than the more recently developed types of molecular markers (microsatellite and AFLP markers).

MAS is based on the identification and use of markers which are linked to the gene(s) controlling the trait of interest (FAO, 2003). By virtue of that linkage, selection may be applied to the marker itself. The advantage consists in the opportunity of speeding up the application of the selection procedure. For instance, a character which is expressed only at the mature-plant stage, may be selected at the plantlet stage if selection is applied to a molecular marker. Also, selection may be applied simultaneously to more than one character, and selection for a resistance gene can be carried out without needing to expose the plant to the pest, pathogen or deleterious agent. Finally, when there is linkage between a molecular marker and a quantitative trait locus (QTL), selection may become more efficient and rapid. The construction of detailed genetic and molecular maps of the genome of the species of interest is a prerequisite for most forms of MAS. However, the current cost of the application of these techniques is significant, and the choice of one technique rather than others may be dictated by cost factors. There are still very few examples of crop varieties in farmers' fields which have been developed based on MAS, largely because of the currently prohibitive cost of incorporating large-scale MAS into the budgets of most plant breeding programmes.

In addition to MAS, molecular markers can be used in germplasm characterization. Compared to morphological and protein markers, DNA-based genetic markers are often considered to be the most useful for genetic diversity studies because they are highly polymorphic and heritable (their expression is not affected by environmental variability). The FAO-BioDeC indicates that molecular markers are being extensively used in Latin America (Table 4) with 93 trials and 165 molecular marker projects at the research phase in nine countries. The assessment of the genetic diversity of Andean local roots and tubers in Latin America using molecular markers is an interesting development. Species reported to be included in molecular marker programmes in these countries are sugar cane, rice, cocoa, banana, bean and maize. The survey also indicates that most countries in Asia are undertaking a wide spectrum of crop research using molecular markers. Molecular marker-related research activities in Africa are reported to be underway in only a few of the countries, such as Ethiopia, Nigeria, South Africa and Zimbabwe; the range of Africa crops under study with molecular markers, however, is very wide: from traditional commodities to tropical fruits.

3.4 DNA AND IMMUNO-DIAGNOSTIC TECHNIQUES

Many crop diseases are difficult to diagnose, especially at the earliest stages of infection by the pathogen. In particular, many diseases caused by viruses can exhibit similar symptoms and therefore it is difficult to identify the causative virus. Knowledge of the nature of the pathogen can be used to develop and apply proper management practices. For instance, some viruses are seed transmitted

TABLE 4
Number of research initiatives to develop and use molecular markers

Technique	Region																													
	Africa					Asia					Eastern Europe					Latin America					Near East					Total				
	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N
RFLP	-	-	5	-	5	-	-	4	1	2	-	5	12	-	5	2	13	20	-	7	-	-	1	-	1	2	18	42	1	20
RAPD	-	-	7	-	5	-	-	10	6	6	-	6	15	-	5	-	39	63	-	8	-	-	16	-	6	-	45	111	6	30
Microsatellites	-	-	1	-	1	-	-	3	11	5	-	-	2	-	2	-	9	31	-	5	-	-	12	-	5	-	9	49	11	18
AFLP	-	-	2	-	2	-	-	3	-	1	-	2	1	-	2	-	8	31	-	6	-	-	14	-	5	-	10	51	-	16
Other	-	-	20	-	8	-	-	13	10	6	-	1	-	-	1	-	24	20	-	6	-	-	2	-	1	-	25	55	10	22
Total	-	-	35	-	12	-	-	33	28	9	-	14	30	-	7	2	93	165	-	9	-	-	45	-	6	2	107	308	28	43

C: technology used on a routine basis and products available on the market; T: results being tested; E: number of activities at experimental level (including laboratory or glasshouse activities); U: activities in unknown phase; N: number of countries involved. (Totals of this column have been calculated taking into account that sometimes more than one activity is being carried out by the same country, although that country will only be counted once).

TABLE 5
Number of initiatives to develop and use diagnostic techniques

Technique	Region																													
	Africa					Asia					Eastern Europe					Latin America					Near East					Total				
	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N
ELISA	-	-	11	-	6	-	-	-	-	-	1	3	9	-	4	-	13	10	1	6	-	-	7	-	5	1	16	37	1	21
Monoclonal antibodies	-	-	2	-	2	-	-	3	-	2	-	-	2	-	2	-	-	-	-	-	-	-	-	-	-	-	-	7	-	6
Nucleic acid	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	1	-	-	1	-	1
PCR	-	-	5	2	7	-	-	2	-	1	-	-	10	-	4	-	4	12	-	3	-	-	2	-	1	-	4	31	-	16
Other	-	-	10	-	8	-	-	2	4	5	-	-	-	-	-	-	-	1	-	1	-	-	2	-	1	-	-	15	4	15
Total	-	-	28	2	10	-	-	7	4	7	1	3	21	-	6	-	17	23	1	7	-	-	12	-	6	1	20	91	5	36

C: technology used on a routine basis and products available on the market; T: results being tested; E: number of activities at experimental level (including laboratory or glasshouse activities); U: activities in unknown phase; N: number of countries involved. (Totals of this column have been calculated taking into account that sometimes more than one activity is being carried out by the same country, although that country will only be counted once).

whereas others are not, or some bacterial pathogens can be managed by changing the growing environment.

The development of cheap diagnostic techniques could assist decision-making in relation to pest and disease management. The development of diagnostic kits, such as enzyme linked immunosorbent assay (ELISA), and other molecular assays, can enable the precise identification of viruses, bacteria and other disease-causing agents, and is now an established tool in disease management in many farming systems. Diagnostic assays have also been developed to identify a wide range of other organisms, chemicals (such as undesirable by-products, e.g. aflatoxin), or impurities involved with food quality.

The FAO-BioDeC (Table 5) suggests that ELISA is only in commercial use in Eastern Europe, although this is unlikely to be unique to Eastern Europe as ELISA is undoubtedly used in plantation farming in many other regions. Most of the use of ELISA reported in Eastern Europe is to detect plant viruses (e.g. PLRV, PVX, PVA, PVM, PVY) in crops such as potato, fruits and strawberries. In the Near East, all ELISA-related work is reported to be in the experimental phase, with Iraq, Morocco and the Syrian Arab Republic working on potato, Morocco also on sugar cane, Tunisia on grapevine and Egypt on detection of ZYMV in cucurbits. In Africa, use of ELISA for cassava diagnostics is under study in Malawi, Nigeria, Uganda and Zimbabwe, for cowpea in Cameroon and Nigeria, and maize in South Africa and Zimbabwe. In Latin America, Brazil is testing ELISA in sugar cane, potato, plum, unspecified *Solanaceae* and soybean, and researching cucurbits, *Solanaceae*, and *Rhizobium* in association with beans and forage and tree legumes, Chile is researching potato, tomato, tobacco and grapevine, Paraguay is testing ELISA in citrus, and Peru is testing potato.

DNA diagnostics are also a powerful technique for identification of pathogens and other organisms in agriculture. Most DNA diagnostics are now based on the use of the polymerase chain reaction (PCR), a common research tool used in most molecular biology laboratories worldwide, which can be used to specifically amplify segments of DNA. Most PCR techniques require the use of the enzyme *Taq* polymerase which until recently was protected by patents requiring that any commercial use of the PCR technique would have to pay royalties to the holders of the *Taq* polymerase patent. The enzyme *Taq* polymerase is now in the process of becoming a 'generic' biochemical reagent which will substantially reduce the cost of PCR applications in research and commerce.

At present, most of the reported work on PCR diagnostics is in the experimental phase. In the Near East, Egypt is working on PCR analysis of ZYMV in cucurbits and TYLCV in tomato. In Europe, Yugoslavia is researching PCR for PPV in plum, ASPV in apple and PVYV in pear. Armenia is working on diagnostic techniques for disease of tobacco, potato, linen, wheat and other crops, Azerbaijan on chickpea, tobacco and other crops, and the Republic of Moldova on maize, tobacco and other crops. In Africa, maize disease diagnostics is the subject of PCR studies in South Africa, Uganda and Zimbabwe, while diagnosis tools are studied for diseases of cowpea in Cameroon and Nigeria, cassava in South Africa and unspecified work is underway in Burkina Faso and Ghana. In Latin America, Brazil is researching on PCR for unspecified uses in sugar cane, bean, rice, tomato, carrot, unspecified Solanaceae and banana and is conducting experiments on sweet potato, garlic, apple, genome sequencing of *Herbaspirillum* in soybean, *Rhizobium* in association with beans and forage and tree legumes, peanut and wild related species, studies on fungi, eucalyptus, Brazilian forest trees, soybean, coffee, sugar cane, *Xylella fastidiosa*, and heart of palm for food quality. Chile is researching molecular diagnostics for pathogens of potato, tomato, tobacco and grapevine, and Peru of potato.

4. Analysis of the FAO-BioDeC data on genetically modified (GM) crop varieties

This section contains an analysis of the data gathered to date on transgenic plant varieties which are resistant to pathogens, pests, herbicides, tolerant to abiotic stresses, and with modified quality traits.

4.1 TRANSGENIC CROP VARIETIES RESISTANT TO PATHOGENS

The data contained in the FAO-BioDeC related to transgenic varieties resistant to pathogens are summarized in Table 6. These data suggest that most pathogen-resistance development programmes oriented towards the development of genetically modified (GM) plant varieties, are concentrated on generating resistance to viruses and fungi, particularly in Asia and Latin America, with very little activity devoted to developing transgenic crop varieties resistant to bacteria.

The current emphasis on viruses most likely reflects the relative simplicity of viral genomes, and the generic 'proof of concept' of virus-derived strategies such as coat protein and replicase-mediated resistance in generating virus-resistant transgenic varieties.

Transgene-mediated resistance strategies against fungi are still in their infancy. Overall, it is unclear from the available data in the inventory why transgenic approaches are more predominant for fungal compared to bacterial pathogens, or why some regions report more research initiatives than others.

Although planting disease-resistant varieties is one of the better ways of combating viruses, bacterial and fungal plant pathogens, as with all biotic stresses with the capacity to mutate and evolve, it would be prudent to develop resistance management strategies to limit the incidence of selection for resistance-breaking pathogen isolates.

4.1.1 Development of transgenic crop varieties resistant to viral diseases

In the case of virus resistance, conventional strategies to control viral diseases are limited to the production of virus-free propagation material and to the control of insects transmitting virus pests. While some crop gene pools harbour resistance to viruses, there are crop gene pools which are completely lacking in resistance against key virus pathogens. The figures in Table 6 suggest a rapid adoption in some regions of pathogen-derived transgene-mediated virus resistance strategies, which were first demonstrated in greenhouses in 1986 for tobacco mosaic virus (TMV) (Beachy, 1999). The few examples of large-scale plantings of virus resistant

BOX 1

The impact of biotic and abiotic stress factors in crop production

Comparisons of attainable and actual yields demonstrate that most crops are at best only reaching 20 percent of the genetic potential for yield (Boyer, 1982). The reductions in yield are attributed to both biotic (e.g. pests, pathogens and weeds) and abiotic stresses.

Out of a US$1.3 trillion annual food production capacity worldwide, the biotic stresses caused by insects, diseases and weeds cause 31–42 percent loss (US$500 billion), with an additional 6–20 percent (US$120 billion) lost post harvest to insects and to fungal and bacterial rots. Crop losses due to pathogens are often more severe in developing countries (e.g. cereals, 22 percent) when compared to crop losses in developed countries (e.g. cereals, 6 percent) (Oerke *et al.*, 1994).

Weeds are also a major and continuing biotic constraint affecting cropping systems worldwide.

Another 6–20 percent (US$120 billion) is estimated to be lost to abiotic causes (drought, flood, frosts, nutrient deficiencies, various soil and air toxicities). One of the most significant abiotic stress reducing crop yields is water stress, both water deficit stress (drought) and excess water stress (flooding, anoxia). It is in this context that the need arises to develop crops which are more resistant to biotic and abiotic stresses.

When crop losses due to biotic or abiotic stresses are known with a reasonable degree of accuracy, resource allocation decisions can be taken regarding which loss prevention approaches may be necessary and what level of resources should be applied to addressing the problem (by biotechnology or other means).

GM varieties should be monitored to determine if resistance breaking variants of the virus pathogens are being selected over a number of growing seasons for large scale crop populations.

In Africa, only three crops, sweet potato, potato and maize, have so far been targeted for transgene-mediated virus resistance. The FAO-BioDeC indicates only two transgenic varieties that to date have been tested in a field trial, namely, a sweet potato variety for resistance to sweet potato feathery mottle virus (SPFMV) in Kenya and a potato variety for resistance to potato leaf roll virus (PLRV) in South Africa. The FAO-BioDeC currently reports only three other research initiatives in an experimental phase in South Africa, namely, the development of potato for resistance to potato virus Y (PVY) and potato virus X (PVX), and development of maize resistant to the maize streak virus (MSV). The inventory indicates that no virus resistant GM varieties have been commercially released in Africa.

In the Eastern and Central Africa region, maize is a major staple of the rural and urban poor. In the same region, potato has become a major highland cash crop and a food staple in some urban areas. Sweet potato is an important crop

TABLE 6
Number of initiatives to develop GMOs with resistance to pathogens

Trait	Region																													
	Africa					Asia					Eastern Europe					Latin America					Near East					Total				
	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N
Virus	-	2	3	-	2	2	17	14	9	9	-	-	-	-	-	-	16	26	-	9	-	9	2	-	3	2	44	45	9	23
Bacteria	-	-	-	-	-	-	1	3	5	5	-	-	-	-	-	-	-	1	-	1	-	-	-	-	-	-	1	4	5	6
Fungi	-	1	1	-	1	-	1	6	-	5	-	-	3	-	1	-	6	16	-	8	-	-	-	-	-	-	8	26	-	15
Other	-	-	-	-	-	-	-	7	-	4	-	-	1	-	1	-	3	8	-	4	-	-	-	-	-	-	3	15	-	8
Total	-	3	4	-	3	2	19	35	14	9	-	-	4	-	1	-	25	51	-	9	-	9	2	-	3	2	56	96	14	25

C: number of GM varieties released as commercial varieties; F: number of GM varieties in field trials; E: number of activities at experimental level (including laboratory or glasshouse activities); U: number of GM varieties at unknown status; N: number of countries involved (for the total column of N, if more than one activity is being carried out by a given country, the country is only counted once).

in the countries surrounding Lake Victoria (Burundi, the Democratic Republic of the Congo, Kenya, Rwanda, United Republic of Tanzania and Uganda). The FAOSTAT database indicates that the 2003 production in Africa for sweet potato was 10 787 127 tonnes, potatoes 12 530 119 tonnes and maize 43 522 313 tonnes. Indigenous to Africa and its offshore islands, MSV causes yield losses of up to 100 percent even in high potential agricultural zones. MSV is considered the most serious virus threat to maize production in Africa, while SPFMV is a serious constraint to sweet potato production.

In the Near East region, Egypt is conducting field trials on virus-resistant GM varieties of potato, tomato, cucumber, melon, muskmelon, cantaloupe, squash and sugar cane. Tunisia has initiated virus-resistant GM research work on potato and *Vitis,* and The Islamic Republic of Iran has initiated this research work on sugar beet. Most virus-resistant GM varieties under field testing are of imported origin. However, one country in this region, Egypt, is carrying out field testing of locally developed virus resistant varieties, mainly cucurbits with resistance to ZYMV, and potato resistant to PVY and PLRV.

At least two virus-resistant transgenic crop varieties have been commercially released in the Asia region. These include virus-resistant tomato and green pepper varieties in China. In general, current research efforts to develop transgenic virus-resistant crop varieties in this region are mostly focused on *Solanaceae*, *Cucurbitaceae* and tropical fruit trees. Special attention is being given to development of virus-resistant papaya, as transgenic papaya varieties resistant to papaya ringspot virus (PRSV) now provide an additional strategy to restore papaya cultivation in areas where the virus has been most destructive (e.g. in Hawaii where major successes have been reported). Research has been reported in Malaysia, the Philippines and Thailand on the development of different ring spotvirus resistant transgenic varieties of papaya, some being combined with delayed fruit ripening.

Field trials are being conducted in China for transgenic varieties exhibiting resistance to: CMV in sweet pepper, CMV and TMV in chilli pepper, TMV in tobacco, PRSV in papaya, stripe virus in groundnut, PVY in potato, BYDV in wheat and turnip mosaic virus in Chinese cabbage. Laboratory stage research work on RDV in rice and WYMV in wheat is in progress in China. Thailand has field trials in progress for transgenic virus resistant varieties of tomato (TYLCV), papaya (PRSV) and pepper (CVbMV), and laboratory stage work on pepper (PepLCV), yard long bean (aphid-borne mosaic virus) and rice (ragged stunt virus). The Philippines has field trials underway for virus-resistant transgenic varieties of banana (BTV), and laboratory stage experimental work on transgenic papaya (PRSV). Indonesia has laboratory research underway on the development of virus-resistant peanut (peanut stripe virus), tobacco (TMV), sweet potato (SPFMV), chilli pepper, papaya and potato (PVX and PVY) varieties. Malaysia is conducting transgenic experiments on the development of virus-resistant rice (tungro virus), papaya (PRSV), pepper (CMV) and chilli pepper, while Bangladesh is undertaking research on papaya to develop transgenic cultivars resistant to papaya mosaic virus. India and Pakistan are currently working on the development of virus-resistant rice, cotton, as well as tomato (Pakistan only).

Of all the regions covered by the FAO-BioDeC, Latin America has the highest number of reported research activities regarding the development of transgenic virus-resistant crop varieties. The FAO-BioDeC indicates that nine countries in Latin America are conducting research and/or development on transgenic virus-resistant crop varieties: Mexico (14 reported activities), Brazil (13), Cuba (four), Argentina (two), Colombia (two), Peru, Chile and Costa Rica (two each), and Venezuela (one). No virus-resistant transgenic crop variety has been reported to be commercially released in this region. In Brazil, field trials are underway for virus-resistant transgenic varieties of sugar cane (SCMV, yellow virus), potato (PVY, PLRV), papaya (PRSV), tobacco (TSWV, PVY), bean (bean golden mosaic virus), *Solanaceae* (isolation of virus resistance genes), and tomato (Gemini and Tospovirus), and laboratory stage experiments are underway on virus-resistant sugar cane. Mexico has virus-resistance trials underway on varieties of papaya (PRSV), potato (PVY and PVX), squash (PAMV, SMV2 and ZaMV), tobacco (TMV), zucchini (PMV, PAMV, SMV2 and ZaMV), melon (CMV), and tomato (CMV). In Cuba, field trials of virus-resistant varieties of papaya (PRSV), and experiments on potato (PLRV), citrus (tristeza virus), and tomato (Gemini virus) are underway. Laboratory stage experiments to develop virus-resistant transgenic varieties are ongoing in Chile for potato and melon, in Costa Rica for rice and maize, in Venezuela for coffee and in Peru for potato and sweet potato.

The large number of research activities reported in the FAO-BioDeC, regarding genetic engineering approaches to generate virus-resistant crop varieties indicates that the basic molecular techniques are well established to develop transgene-cassette based approaches for control of most crop viruses. This basic molecular biology capacity is seemingly available in many of the countries covered by the database and the transgene cassettes can often be developed or obtained through collaboration with partner laboratories in other countries with more advanced research capacity. The rapid adoption of this technology within the context of broader agricultural R&D reflects the widespread occurrence of viruses across the regions and crop species, and the difficulty of controlling crop viruses by conventional (non-transgenic) means.

4.1.2 Development of transgenic crop varieties resistant to bacterial diseases

The FAO-BioDeC provides details on the use of genetic engineering for the development of bacterial-resistant transgenic crop varieties. The results suggest a low level of R&D activity in this area in the five regions. Just one transgenic variety with enhanced bacterial resistance is reported as being under field trial - a potato variety with wilt resistance in China. However, laboratory stage research initiatives to develop bacterial resistant crop varieties are reported in six countries: in China (potato and wheat wilt resistance); in Thailand (bacterial wilt and other resistances in tomato); blight resistance in Basmati rice in Pakistan; leaf blight in rice, potato and cabbage in the Republic of Korea ; and also bacterial-resistance work on jute in Bangladesh and banana in Venezuela.

The lower level of activity on resistance to bacterial diseases compared to other diseases may be due to both a lower perception of the importance of bacterial diseases and the number of crops infected by them compared to the incidence of viral diseases, and to more readily available alternative technologies to combat bacterial diseases.

4.1.3 Development of transgenic crop varieties resistant to fungal diseases

Some of the most devastating and universal crop diseases are caused by fungal pathogens (Box 2). For instance, the rust fungi are the most widespread and generally cause the largest crop losses per season. Crop losses can be considerable due to fungal pathogens. For example, the fungal agent of rice blast disease (*Magnaporthe grisea)* destroys 157 million tonnes of cultivated rice each year, enough rice to feed 60 million people worldwide (Pennisi, 2001).

The negative effects of some fungal pathogens can be limited by the use of chemical fungicides. Demand for fungicides amongst farmers is high, indicating that for many farmers there are few available alternatives. The world market for agricultural and non-crop fungicides amounted to an estimated US$6 billion at the end-user level in 1999. The United States, Western Europe and Japan together accounted for 75 percent of the total world market. Small grains constitute the largest market for fungicides worldwide. This sector accounted for an estimated 27 percent of the total world market in 1999, followed closely by tree and vine crops (24 percent), rice (16 percent), and vegetables and potatoes (10 percent). Other crop markets accounted for 17 percent of the world fungicide market, and non-crop markets accounted for 6 percent.

BOX 2

Fungal diseases of some important crops worldwide

Cereals	Powdery mildew, rusts, leaf-spot diseases, common bunt of wheat, loose smuts
Rice	Blast, sheath blight and other leaf spot diseases
Vegetables	Leaf rot, brown rot, grey mould, powdery mildew and downy mildew, leaf spot and fruit spot diseases (e.g. *Alternaria*)
Potatoes	Late blight, early blight (*Alternaria*), black scab (*Rhizoctonia*), silver scurf
Grapevine	Powdery mildew (*Oidium*) and downy mildew (*Peronospora*), grey mould (*Botrytis*)
Peanuts	White mould (*Rhizoctonia*), *Sclerotinia* stem rot, leaf spot, rust
Banana	Sigatoka leaf spot
Coffee	Coffee rust

In many countries, fungicides as crop protection products are subject to strict legislative regulation and undergo a rigorous and expensive process of registration for public sale. While fungicides can provide a level of control, this chemical option is often limited for many farmers, particularly in developing countries, by high costs and lack of knowledge about application. In addition, the negative effects of fungicide applications on human health, with special reference to the labourers and the environment can be considerable. There is a need to find more environmentally benign alternatives to fungicides to control fungal diseases of crops.

Genes can be identified that confer resistance to fungal pathogens. For instance, many genes have been found that provide resistance to specific races of each rust pathogen. In many cases, resistance genes are available in the gene pool of cultivated plants and can be transferred to them by cross-breeding programmes. The incorporation of plant-derived resistance genes against fungal pathogens into susceptible varieties could allow development of resistant varieties which can deliver high yields in the absence of fungicide applications.

Actual and potential access by farmers to traditional fungal control measures such as fungicides, and the absence of durable transgenic genetic resistance strategies, may explain why there are few reported efforts to develop transgenic varieties which are resistant to fungal pathogens. In relation to fungi, the current stage of successful research worldwide on identification/isolation of genes conferring durable resistance to fungal diseases of crops, is probably not encouraging developing countries with scarce research resources to embark on transgenic approaches to fungal resistance.

In the African region, only two initiatives for fungal resistant transgenic varieties are reported, a field trial of transgenic strawberry with phytoalexin synthesis genes (e.g. *Vst1*, *Vst2*) and laboratory work on transgenic maize for resistance to cob rot (*Stenocarpella maydis*), both in South Africa.. The three initiatives for development of fungal resistant transgenic varieties reported in Eastern Europe were all in Bosnia and Herzegovina where laboratory testing of transgenic potato for resistance to *Fusarium, Verticilium* and *Rhizoctonia* has been initiated. In the Asian region, there is a field trial underway in China for transgenic cotton with resistance to *Verticilium* and *Fusarium*. Other R&D initiatives reported include the involvement of India, Malaysia and Pakistan in research on sheath blight of rice, and of Indonesia on rice blast and leaf rust of coffee.

A few countries in Latin America, mainly Argentina, Brazil and Cuba, are carrying out a number of activities on transgenic resistance to fungi, particularly on tropical fruit trees, with some results already being tested in the field. In this region, most of the activities for transgenic fungal resistance are reported in Cuba, in particular involving field trials of transgenic potato for late blight resistance, and fungal-resistant sugar cane. Other field trials in the Latin America region for transgenic fungal resistance are reported for maize, sunflower and wheat in Argentina, and tobacco in Mexico. Other crops subject to transgenic R&D for fungal resistance in Cuba are banana, plantain, pineapple, tomato, papaya, citrus and rice. Other countries involved in transgenic fungal resistance research are

TABLE 7
Number of initiatives to develop GMOs with resistance to pests

Trait	Region																													
	Africa					Asia					Eastern Europe					Latin America					Near East					Total				
	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N
Coleoptera	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lepidoptera	2	1	1	-	3	3	15	11	6	7	-	-	-	-	-	1	17	5	-	6	-	2	2	-	2	6	35	19	6	18
Other	-	-	2	-	2	-	1	6	8	5	-	-	-	-	-	-	3	10	-	5	-	-	1	-	1	-	4	19	8	13
Total	2	1	3	-	3	3	16	17	14	7	-	-	-	-	-	1	20	15	-	10	-	2	3	-	2	6	39	38	14	22

C: number of GM varieties released as commercial varieties; F: number of GM varieties in field trials; E: number of activities at experimental level (including laboratory or glasshouse activities); U: number of GM varieties at unknown status; N: number of involved countries. (Totals of this column have been calculated taking into account that sometimes more than one activity is being carried out by the same country, although that country will only be counted once.)

Argentina on alfalfa, Brazil on rice, barley and cocoa, Chile on grape and apple, Colombia on tree tomato, Peru on potato for late blight resistance and Venezuela on sugar cane.

4.2 DEVELOPMENT OF TRANSGENIC CROP VARIETIES WITH ENHANCED RESISTANCE TO PESTS AND HERBICIDES

4.2.1 Resistance to insect pests

Insects consume a large share of food and fibre destined for humans (pre- and post-harvest). The worldwide economic damage caused by insect pests to agricultural and horticultural crops and to orchards stands at a hundred billion dollars annually (Ulenburg, 2000). The strategies to limit the damage from insect pests fall into three categories:

(1) Treatment of crops and their pests with chemical insecticides. Drawbacks of the use of chemicals are the development of resistance by the insects to the insecticides and secondly, the toxicity of many pesticides for the environment and human health.

(2) Development of insect-resistant crops by hybridization or by transgenic modification. While transgenic approaches to the development of insect resistance are likely to be the fastest route, or the only means when pest resistance is not available in the genetic pool of the crop plant considered, they are more controversial, as with all genetic modifications of crop plants.

(3) Introduction of natural enemies (usually alien species introductions) to further biological balance with limited damage. This approach is limited by the availability of natural enemies of the target pest and often risky as it is difficult to predict the outcome of the changes in the agro-ecological niche.

For all these strategies, it is important to gain good knowledge of the pest species that may cause damage at a certain place and time. Quick and reliable identification of the species and monitoring of their geographical distribution and life history is the basis of all effective policies to control insect pests. Worldwide, there are several thousands of insect pest species known to affect a range of crop species, each with their own characteristic damage, distribution and natural enemies. The knowledge and expertise in this scientific field is still limited and often insufficient to develop effective control strategies, especially in tropical or subtropical environments which characterize most developing countries.

Development of transgenic crop varieties resistant to Lepidopteran pests

Among the insect pests, *Lepidoptera* represent a diverse and important group. The FAO-BioDeC indicates that most insect-resistant transgenic crop varieties under R&D are obtained for the control of *Lepidoptera* (Table 7), predominantly using transgene cassettes including a toxin-producing gene from the soil bacterium *Bacillus thuringiensis (*Bt) see Box 3.

In Asia, *Lepidoptera*-resistant cotton varieties developed using Bt transgenes have been commercially released in China, India and Indonesia and field trials are

BOX 3

Bt gene deployment for managing genetic resistance to pests

The insect-resistant transgenic crop varieties reported in the FAO-BioDeC to date are mostly based on the expression of *Bacillus thuringiensis* (Bt) genes encoding for the production of biocontrol toxins, that have been previously confirmed to control different *Lepidoptran* pests in different crops, such as corn earworm, boll worm, farm armyworm, tuber moth, leaf miner, stem borer, brown plant hopper or *Paraserlanthes* sp. Like all biotic stresses (e.g. viruses, bacteria, fungi), insect pests have the capacity to evolve and the widespread use of the same monogenic control strategies (e.g. the same type of Bt toxin) can result in selection for resistance-breaking strains of the insect pest. Resistance to conventional spray applications of Bt formulations has been observed in the diamondback moth (*Plutella xylostella*) (Tabashnik ,1994) and demonstrated in the laboratory for other species. This resistance build up is now of particular concern since, with the advent of Bt transgenic crops, the selection pressure for resistance will be greatly increased for a number of crop pests. To prevent or delay the emergence of insect resistance to Bt crops, insect resistance management programmes have been put into place. These include the use of structured non-treated refuges, high toxin dosage, mixtures of insecticidal proteins and rotation or alternation of Bt toxins (Nester *et al.*, 2002).

Continuing research must be encouraged in developing countries in order to identify other genetic resistance options (including deployment modes) for a more complete and stable pest control, especially for those crop species specific to their environment and economy. For example, in addition to Bt genes, protease inhibitors, neuropeptides and peptide hormones that control and regulate the physiological processes of several insect pests may become candidates for this purpose. Other biocontrol toxins currently studied are chitinases, lectins, alpha-amylase inhibitors, cystatin and cholesterol-oxidase and glucosidase inhibitors. Cotton with CpTI in combination with Bt is being grown in China and Brazil is also combining other resistances with Bt.

underway in Thailand. Other field trials underway in China involve local varieties of rice containing Bt transgenes, transgenic cotton expressing Cowpea Trypsin Inhibitor (CPTI), rice transformed for resistance to stem borer and yellow borer, maize for corn borer, cotton for bollworm, and poplar for gypsy moth. Bt tobacco is also in field trials in India and Bt maize in Indonesia. Laboratory stage research work is ongoing in Asia on potato to generate resistance to tuber moth in India and Indonesia, diamond back moth (cabbage) in India, in addition to generation of resistance to *Lepidopteran* pests of cotton, rice and chickpea in Pakistan. Bt maize has been commercially released in the Philippines, research is underway in Indonesia on transgenic maize for corn borer, soybean for pod borer, rice for stem borer, *Cacao* for fruit borer, sugar cane for stemborer and oil palm for S*etothosea asigna*. Research is also ongoing on transgenic cotton for bollworm resistance in China and Thailand, jute for hairy caterpillar in Bangladesh, soybean in China and Chinese cabbage in the Republic of Korea .

In Latin America, transgenic maize resistant to *Lepidopteran* pests has been released in Argentina, and is in field trials in Brazil and Mexico, and undergoing laboratory testing in Cuba. Other field trials are underway on transgenic soybean in Argentina and Brazil, and cotton in Bolivia, Brazil and Mexico, potato in Mexico and Peru, sugar cane in Brazil and Cuba, tomato in Mexico, sweet potato in Cuba and sunflower in Argentina. Laboratory stage work on transgenic resistance to *Lepidiopteran* pests of rice, coffee and pineapple is ongoing in Cuba and on sugar cane in Brazil.

In the Near East there are field trials of *Lepidoptera*-resistant transgenic varieties of maize and potato in Egypt and rice in the Islamic Republic of Iran , and laboratory work on cotton and maize in Egypt and the Islamic Republic of Iran, respectively. Only four activities to generate *Lepidoptera*-resistant transgenic varieties are reported for Africa. Both *Lepidoptera*-resistant transgenic maize and cotton are under commercial cultivation in South Africa, and laboratory work is underway in Kenya. Transgenic Bt cotton is reported to be under field trial in Zimbabwe.

The rapid adoption of the use of Bt derived transgenes for development of pest-resistant crop varieties, suggests that this approach has generated a new and valuable option for control of some crop pests, which can be applied across a range of agro-environments, crop species and pests.

Development of transgenic crop varieties resistant to Coleopteran pests

Beetles and weevils are also important insect pests of crops. A wide range of beetles are of economic importance since they interfere with agricultural and forestry crops, timber products and stored products, etc. However, beetles do not transmit any diseases of humans or livestock. Due to the fact that there are many predators, herbivores and scavengers amongst the beetles, they play an important role in maintaining the ecological balance in natural systems. Furthermore, many host-specific species are used as biocontrol agents of insect pests and noxious weeds.

As an example of *Coleoptera*n pests, the African sweet potato weevils (*Cylas puncticollis* and Cylas *brunneus*) are major pests of sweet potato production in sub-Saharan Africa. Sweet potato crop losses due to weevils range from 20-100 percent with more severe losses reported in the dry season or during droughts. No genes conferring durable resistance to such weevils have yet been identified within the sweet potato gene pool. The case of sweet potato weevils in Africa is an interesting one regarding decisions on the most effective options for control of the weevils. There are options for the control of other weevils (e.g. *Cylas formicarius*) used in other regions of the world, which are based on the use of pheromones and bio-insecticides. However, control of African sweet potato weevils has not been successful in Africa and bio-insecticides are generally not available or affordable to African sweet potato farmers. In such a context, the generation of weevil resistant crop varieties using transgenic technology presents a new and potentially valuable option for weevil control.

In spite of their agronomic and economic relevance, the FAO-BioDeC (Table 7) suggests that there is no R&D activity to develop transgenic crop varieties which are resistant to *Coleoptera* pests in any of the regions.

4.2.2 Development of transgenic crop varieties resistant to nematode pests

Nematodes are distributed worldwide and live saprotrophically or as parasites of plants, animals and humans. While most nematodes in soil are actually beneficial, farmers are most concerned with nematodes that are pathogens of the roots, stems, leaves or seeds of plants. Plant parasitic nematodes are of great economic importance, they are responsible for over US$100 billion in annual crop losses worldwide (Sasser and Freckman, 1987). They attack a wide variety of plant species, among them many staple crops, vegetables and ornamentals. The root-parasitizing nematodes of the genera *Meloidogyne* (root-knot nematodes), *Heterodera* and *Globodera* (cyst nematodes) are the most important pathogens.

While substantial yield increases have been realized with the discovery and use of nematocides, considerable work remains to be carried out in many aspects of nematode biology and management. On average, only 0.2 percent of the value of crop loss due to nematode damage is invested into nematode research. Furthermore, nematology is a relatively young science and although many crops suffer losses due to nematodes, the number of nematologists working in agriculture is still largely insufficient to properly address this problem. Therefore, much remains to be learned to manage these serious pests.

Due to high crop losses, there is generally a need for the treatment of infested soil with chemical nematocides. Many synthetic chemical nematocides are very unspecific and possess a high general toxicity so that they have been, or will soon be, banned by many governments. Alternative efficient methods to control nematode infestations are rare. Therefore, the search for new nematode control methods is of great economic interest for developing countries.

Strategies deploying crop genetic resistance to nematodes could generate new options for nematode control. The FAO-BioDeC contains no reports in all regions on the use of transgenic technology to develop nematode resistant crop varieties. This was surprising given the high frequency and ubiquity of nematode pest species and the wide range of potential hosting species, across all the regions surveyed. The lack of reports of R&D to develop nematode resistant transgenic crop varieties might be influenced by three factors:

a) the remaining existence on the market of some nematocides that maintain their effectiveness for a considerable number of growing seasons. Many of these nematocides are no longer patent-protected and are available at reasonable cost to some farmers;
b) the limited geographic mobility of the nematode species, which spreads from one field to another very slowly. In many cases, therefore, farmers tend to solve the nematode problem inexpensively by transferring cultivation to other nearby fields; and
c) the slow progress to date in identification of monogenes conferring efficacious resistance to nematodes.

4.2.3 Development of transgenic crop varieties resistant to herbicides for weed control

Adequate systems for weed control are an essential component of all farming systems. Depending on the crop and weeds present, uncontrolled weeds can reduce yields by over 50 percent, impair crop quality, contaminate the harvest with undesirable weed material, and increase the likelihood that the crop will be attacked by insects or diseases. Weeds compete for nutrients and light, especially during the early stages of crop growth, and for moisture in drought stressed areas, often causing severe yield losses. For example, in labour intensive, small farm operations on the Nigerian savannah, weed-related yield losses from 65 to 92 percent have been recorded (IAC, 2004). The parasitic flowering plant known as "witchweed" *(Striga spp.)* remains a major pest of staple crops in sub-Saharan Africa, despite a number of unsuccessful initiatives and considerable research input to find a means of control. The areas infested with parasitic broomrapes (*Orobanche* spp.) and witchweeds are vast and expanding. *Striga* is considered as the greatest single biotic constraint to food production in Africa, where the livelihood of 300 million people is adversely affected. In infested areas, yield losses associated with *Striga* damage are often significant, ranging from 40-100 percent (Bebawi and Farah, 1981; Lagoke *et al.,* 1991; Ejeta *et al.,* 1992). Crop yields could potentially be doubled if such weeds could be controlled. However, labour intensive weeding is largely ineffective against weeds like *Striga*.

Weeds can be controlled mechanically (by cultivation or hoeing), chemically (with herbicides) or agronomically (e.g. crop rotation). In addition to the undesirable effects of weeds on agricultural production, many weeds can also damage natural areas, alter ecosystem processes and facilitate displacement of native species.

Herbicide tolerant varieties provide new options for the control of major weeds which are constraining agricultural production in the regions surveyed. The FAO-BioDeC shows (Table 8) that in relation to herbicide resistant transgenic varieties, the situation is rather different among regions and most of the R&D activity in this area seems to be concentrated in a small number of countries per region. To date, the database suggests that research attention has been focused largely on the development of transgenic crop varieties resistant to glyphosate (Roundup) and glufosinate ammonium (or phosphinothricin, commercialized under the name Basta). There are also reports of some instances of development of crops resistant to herbicides such as bromoxynil, imidazolinone, bialaphos and isoxazoles.

Glyphosate resistance has been most widely used in Latin America, where Roundup-Ready™ (RR) transgenic soybean has been cultivated in Argentina and Uruguay. According to other reports, the same two countries have released two more herbicide-resistant soybean varieties, however, without specification of the kind of herbicide resistance. A glufosinate-resistant transgenic maize variety has also been released in Argentina. Brazil has recently accepted the RR soybean and is now cultivating it on a large scale. Thirty-four herbicide tolerant transgenic varieties are

TABLE 8
Number of initiatives to develop GMOs with resistance to herbicides

Trait	Region																													
	Africa					Asia					Eastern Europe					Latin America					Near East					Total				
	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N
Glufosinate	-	3	-	-	1	-	-	-	-	-	-	-	1	-	1	1	14	5	-	4	-	-	-	-	-	1	17	6	-	6
Glyphosate	-	4	-	-	1	-	4	-	-	2	-	1	-	-	1	3	14	-	-	4	-	-	1	-	1	3	23	1	-	6
Phosphinotricin	-	2	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	1
Other	-	2	1	-	1	-	1	-	6	3	1	-	-	-	1	-	6	6	-	4	-	-	-	-	-	1	9	7	6	8
Total	-	11	1	-	1	-	5	-	6	4	1	1	1	-	2	4	34	11	-	7	-	-	1	-	1	5	51	14	6	15

C: number of GM varieties released as commercial varieties; F: number of GM varieties in field trials; E: number of activities at experimental level (including laboratory or glasshouse activities); U: number of GM varieties at unknown status; N: number of involved countries. (Totals of this column have been calculated taking into account that sometimes more than one activity is being carried out by the same country, although that country will only be counted once.)

being field tested in Latin American countries, particularly in Argentina, Brazil and Mexico. In this regard, field trials have been performed for transgenic cotton, alfalfa, maize, sunflower, sugar beet and wheat in Argentina, maize, cotton, sugar cane and eucalyptus in Brazil, and cotton, maize and soybean in Mexico.

In addition to glyphosate, glufosinate resistant varieties are important in Latin America, where 14 field trials have been carried out in the region on transgenic soybean in Argentina, Brazil and Mexico, sugar cane in Brazil and Cuba, maize in Brazil and Mexico, wheat in Argentina and Mexico, sugarbeet in Argentina, rice in Brazil and potato in Cuba, which also has extensive laboratory input into rice, banana, plantain, coffee and pineapple. However, it must be noted that the number of laboratory research activities in the area of glufosinate resistance is much lower (5), and all such research activities are concentrated in Argentina (barley and sugar cane), Cuba, (rice, banana and plantain, coffee and pineapple) and Venezuela (sugar cane and mango).

In Eastern Europe, field trials on glyphosate and glufosinate tolerant maize are ongoing in Serbia and Montenegro, whereas Bulgaria is commercially cultivating unspecified herbicide tolerant maize. In the Near East, the only research reported is on transgenic canola in the Islamic Republic of Iran. In Asia, Indonesia is conducting herbicide tolerance field tests on imported GM maize, cotton and soybean, and China on soybean. China is conducting research on herbicide tolerant rice, Pakistan on wheat and the Republic of Korea on cabbage, chinese cabbage and potato, though no details are given.

In Africa, the only GM herbicide tolerance research reported in the FAO-BioDeC is taking place in South Africa, with field trials of 11 transgenic varieties resistant to different herbicides. The crops involved included canola, cotton, *Eucalyptus,* lucerne, maize, soybean, sugar cane and strawberry.

In all regions, the higher number of field trials when compared to laboratory stage research in this area, suggests that most of the varieties undergoing field trials are likely to have been generated outside of the regions or result from crosses with local varieties. In addition, the relatively high number of laboratory research in this area compared to e.g bacteria resistance may also reflect the comparative technical simplicity for many species of generating herbicide tolerant crops using transgene cassettes obtained from research institutions or companies with more advanced research capacity.

The limiting factors to R&D to generate herbicide tolerant transgenic crops are the number and type of herbicides and transgene resistance cassettes available, the ease with which the crop species or variety can be transformed, the registration requirements both for the herbicide and the transgenic crop variety, and the level of access of farmers and researchers to proprietary herbicides and transgene resistance cassettes. Yet, the early experiences with herbicide resistant maize to control *Striga* infestations in Africa suggest that novel models to disseminate herbicide tolerant transgenic crops could benefit even resource-poor farmers.

TABLE 9

Number of initiatives to develop GMOs with resistance to abiotic stresses

Trait	Region																													
	Africa					Asia					Eastern Europe					Latin America					Near East					Total				
	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N
Frost	-	-	-	-	-	-	1	-	1	2	-	-	-	-	-	-	1	-	-	1	-	-	-	-	-	-	2	-	1	3
Salt	-	-	-	-	-	-	1	4	2	5	-	-	-	-	-	-	-	2	-	2	-	1	1	-	1	-	2	7	2	8
Heat	-	-	-	-	-	-	-	-	-	-	-	-	2	-	1	-	-	-	-	-	-	-	2	-	1	-	-	4		2
Drought	-	-	1	-	1	-	2	1	2	3	-	-	1	-	1	-	-	-	-	-	-	-	1	-	1	-	2	4	2	6
Other	-	-	1	-	1	-	1	2	1	2	-	-	-	-	-	-	-	7	-	5	-	-	2	-	1	-	1	12	1	9
Total	-	-	2	-	2	-	5	7	6	6	-	-	3	-	1	-	1	9	-	5	-	1	6	-	1	-	7	27	6	15

C: number of GM varieties released as commercial varieties; F: number of GM varieties in field trials; E: number of activities at experimental level (including laboratory or glasshouse activities); U: number of GM varieties at unknown status; N: number of involved countries. (Totals of this column have been calculated taking into account that sometimes more than one activity is being carried out by the same country, although that country will only be counted once.)

4.3 TRANSGENIC VARIETIES RESISTANT OR TOLERANT TO ABIOTIC STRESSES

Abiotic stresses continue to limit crop productivity in every season and in every agro-ecosystem worldwide. Among the abiotic stresses affecting crop production in developing countries, drought and low soil fertility are the most significant. Plants vary tremendously in their ability to withstand abiotic stresses, both between species and within populations of a single species, but the nature of abiotic stress tolerance is not well characterized. Understanding the mechanisms of abiotic stress tolerance will have a significant impact on crop productivity. For instance, crop loss to drought in the tropics alone is thought to exceed 20 million tonnes of grain equivalent per year, or around 17 percent of well-watered production, reaching up to 60 percent in severely affected regions such as southern Africa in 1991-92 (Ribant *et al*., 2002). The development of crop varieties (transgenic or non-transgenic) which can tolerate abiotic stresses would be of major benefit to agriculture in cropping regions where abiotic stresses are a chronic problem.

As shown in Table 9, no transgenic crop variety tolerant to abiotic stress has so far been reported to be released for cultivation in any of the regions covered by the database. However, 7 transgenic varieties exhibiting tolerance to a range of abiotic stresses underwent field testing in Bolivia (a frost tolerant potato variety), China (a cold tolerant tomato), Egypt (a salt tolerant wheat variety), India (moisture stress tolerant *Brassica* variety) and Thailand (salt tolerant and drought tolerant rice varieties). The number of research initiatives at the laboratory stage in this area totals 27.

Most of the R&D activities on development of abiotic stress tolerant crops are being carried out in six countries of the Asian region, namely Bangladesh, China, India, Indonesia, Pakistan and Thailand. China is relatively active in this area, and has reported preliminary successes with rice, maize and sorghum tolerant to high salt concentrations. Transgenic studies on salt resistant crop development are also being undertaken on rice in Bangladesh, Brazil, India and Pakistan, and on tobacco in Argentina. Transgenic research approaches to obtaining aluminium-resistant varieties are underway for wheat in Mexico and sugarbeet in China.

Despite the effects of drought on crop production, very little transgenic research on drought resistance is reportedly being carried out in the five regions. Drought-tolerant rice is currently being field tested in Thailand. The rest of the activities in this area are mainly at the laboratory stage, with work on sugar cane (Indonesia), rice (China and Indonesia), and groundnut (South Africa).

Overall, the extent of R&D reportedly devoted to abiotic stress tolerance is insufficient when compared to the well known needs for abiotic stress tolerant varieties in the regions surveyed. For instance, vast areas of soils containing an excess of heavy metals are present in Brazil and Africa. Also, a steadily increasing acreage of agricultural land in Asia and elsewhere is becoming agriculturally sterile because of salinity brought about by poorly managed irrigation practices. The major limitation is the complexity of tolerance to abiotic stresses that is normally dependent on a number of physiological traits, each under multigenic control.

TABLE 10
Number of initiatives to develop GMOs with improved quality traits

Trait	Region																													
	Africa					Asia					Eastern Europe					Latin America					Near East					Total				
	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N
Vitamin content	-	-	-	-	-	-	-	-	2	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	2
Oil composition	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	-	-	3	-	-	-	-	-		3			3
Protein content	-	-	-	-	-	-	1	1	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		1	1		2
AA composition	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	-	-	3	-	-	-	-	-		3			3
Starch composition	-	-	-	-	-	-	-	2	-	2	-	-	1	-	1	-	-	-	-	-	-	-	-	-	-			3		3
Altered growth traits	-	-	-	-	-	1	2	5	-	4	-	-	-	-	-	-	6	1	-	2	-	-	1	-	1	1	8	7		6
Other	-	-	-	-	-	1	-	19	2	6	-	-	9	-	5	-	7	11	-	7	-	-	-	-	-	1	7	39	2	18
Total	-	-	-	-	-	2	3	27	4	8	-	-	10	-	5	-	19	12	-	8	-	-	1	-	1	2	22	50	4	22

C: number of GM varieties released as commercial varieties; F: number of GM varieties in field trials; E: number of activities at experimental level (including laboratory or glasshouse activities); U: number of GM varieties at unknown status; N: number of involved countries. (Totals of this column have been calculated taking into account that sometimes more than one activity is being carried out by the same country, although that country will only be counted once.) AA: amino acid

The increased wealth of knowledge that is being acquired by means of genomics, mainly functional genomics, and other molecular biology studies, will certainly contribute to the development of tolerant genotypes.

4.4 TRANSGENIC VARIETIES WITH MODIFIED QUALITY TRAITS

The nutritional and economic value of many grain crops depends on the quantity and types of compounds (e.g. protein, starch and oil) that accumulate during seed development. Plant breeders have long strived to develop new crop varieties with enhanced quality trait profiles.

The results shown in Table 10 describe the different situations, regarding the development of transgenic crops with enhanced quality traits in each region. No research or field testing activity is reportedly taking place in the African or Near Eastern regions, despite well-known dietary deficiencies prevailing in both regions. However, this situation is not paralleled in Asia, where a total of 34 activities on this topic are reported in eight countries or in Latin America where 31 reported initiatives in eight countries. In Latin American countries, there are 12 research activities reported and 19 transgenics under field testing, mostly in Argentina and Mexico.

A wide range of characteristics can fall under the topic of 'quality trait' and the use of this loose term in a survey can result in different categorizations by different respondents. For instance, the reports from Latin America indicate that there are field trials of varieties with enhanced quality traits underway on rice (Sucrose-phosphate synthase) and other trials for unspecified characteristics are underway on soybean in Argentina, and canola and flax in Mexico. Laboratory studies cover alfalfa (veterinary edible vaccines), *Paspalum dilatum* (foddering quality), *Triticale* (biomass production) in Argentina, eucalyptus (reduction of lignin content) and *Psychotria* spp. (improved alkaloid production) in Brazil, sugar cane (altered lignin content and high quality sugar) in Cuba, *Echinacea*e, *Psychotria* and *Tagetes* (alkaloid production) in Costa Rica, and improvement of flour quality and reduction of natural toxicants in potato in Peru.

Quality traits also exist in the floriculture industry. In this regard, a petunia variety with altered flower colour is now in commercial production in China.

Micronutrient malnutrition, especially lack of iron, zinc and vitamin A, currently afflicts more than half the world's population. Called "micronutrients" because they are needed in only miniscule amounts, these substances enable the body to produce enzymes, hormones and other substances essential for proper growth and development. Tiny though the amounts are, the consequences of their absence are severe. Iodine, vitamin A and iron are most important in global public health terms. Their lack represents a major threat to the health and development of populations the world over, particularly to pre-school children and pregnant women in low-income countries. Enhancing the micronutrient (vitamin and mineral content) status of staple crops is considered to be one approach where crop biotechnology could generate crop varieties that could be used to strengthen food security and prevent malnutrition.

4.4.1 Protein content and amino-acid profiles

Protein-energy malnutrition (PEM) is a most lethal form of malnutrition. Children are its most visible victims. Malnutrition contributes to at least half of the 10.9 million child deaths each year (El-Nawany *et al.,* 2002; World Hunger Facts, 2004). PEM disorders result from a lack of protein and carbohydrates (energy). Cereals and root crops such as cassava form a substantial portion of developing country staple diets, thus improving their protein content and quality will go a long way to curbing the devastating effects of PEM. Seed proteins of many major crops often do not contain sufficient quantities of amino acids essential in the diet of humans and other monogastric animals. As cereals are usually deficient in lysine and tryptophan, and legumes are deficient in the sulphur amino acids methionine and cystine, a mixture of cereals and legumes is used to provide a balance of amino acids in the diet. Breeders at CIMMYT (Mexico) have managed with conventional breeding (over three decades) to develop quality protein maize (QPM) varieties which have enhanced levels of the two 'essential' amino acids, lysine and tryptophan, in the endosperm protein. These new varieties look and taste like normal maize but the nutritive value of their protein is nearly equivalent to cow's milk. Modifying the genes that encode seed proteins by genetic engineering is one additional option to address the problem of nutritional quality in some staple crop varieties.

The FAO-BioDeC does not reveal any significant level of research on metabolic engineering of protein content nor quality in crop varieties in the vast majority of countries surveyed. The only research reported is on field trials for high lysine maize in China. Argentina is also reported to have conducted field trials for unspecified traits in maize and soybeans as well as wheat with high molecular weight glutein.

4.4.2 Vitamin profiles

Vitamins are essential components of the human diet and dietary deficiencies in some vitamins can have tragic effects. For instance, vitamin A deficiency (VAD) is the leading cause of preventable blindness in children and raises the risk of disease and death from severe infections. In pregnant women, VAD causes night blindness and may increase the risk of maternal mortality. It is a public health problem in 118 countries, especially in Africa and South-East Asia, once again hitting hardest young children and pregnant women in low-income countries. Crucial for maternal and child survival, supplying adequate vitamin A in high-risk areas can significantly reduce mortality.

The arsenal of nutritional approaches to combat VAD includes a combination of breastfeeding and vitamin A supplementation, coupled with enduring solutions, such as the promotion of vitamin A-rich diets and food fortification. Among these approaches, biotechnology research has contributed the additional option of increasing the vitamin A content of staple foods which are typically low in vitamin A content. The proof of concept of this approach has been the highly publicized high-beta carotene (pro-vitamin A) rice transgenics recently developed, and currently under dissemination to many NARS, under the name of 'golden rice' and 'golden mustard' in India. Yet, the FAO-BioDeC indicates that there is little R&D underway on enhancement of vitamin content in crop varieties in the regions surveyed.

4.4.3 Mineral profiles

Most staple crops are not considered an important source of minerals in the human or domestic animal diet. Yet, because of the high level of consumption of staples, small increases in the mineral concentration of staples could have a significant effect on human nutrition and health. Iron deficiency anaemia afflicts an estimated 1.5 billion people in developing countries, most of them women, reducing mental ability, creating severe complications at childbirth, and lowering physical capacity. Zinc deficiency, though less well understood, is also known to be widespread in the tropics and is a major threat to children's growth and health. The nutritional quality of staple crops (rice, cassava, wheat, maize and beans) in terms of mineral content can be improved by both conventional breeding and/or biotechnology. Currently the FAO-BioDeC does not report any biotechnology activity targeted towards the improvement of crop mineral profiles in developing countries.

4.4.4 Oil composition

It seems from the countries covered by the FAO-BioDeC that the modification of plant oil and wax composition has received little attention. Among the instances of R&D in this area are ongoing field trials in Argentina on maize and soybean, and in Mexico on canola expressing high levels of lauric acid. In addition, there is ongoing laboratory work on oil palm with low saturated fatty acids in Indonesia and Malaysia and high lauric acid content in coconut in the Philippines. Furthermore, in Malaysia there is development of oil palm with special oils for the production of biodegradable plastics.

4.4.5 Plant growth traits

The genetic manipulation of the metabolic routes leading to plant hormone (e.g. ethylene) synthesis and degradation can induce modifications of plant organ maturation. Such control of maturation can allow the production of fruits showing resistance to postmaturation deterioration, resulting in the ability to be transported without refrigeration, extended shelf life and improved quality. For many developing countries with limited refrigeration capacity and transport infrastructures, this research avenue is extremely promising, insofar as it improves flexibility of transport of otherwise perishable products to distant markets and on poor routes. Most of the research reported on alterations in plant growth has concentrated on delayed fruit ripening. In Latin America, Mexico reports a large number of field trials for altered growth in varieties of crops such as tomato (two approaches), chilli pepper, banana, melon, papaya and pineapple. In this area, Chile has a laboratory research initiative on stone fruits. In Asia, papaya varieties with altered growth traits are under laboratory study in China, Indonesia and the

TABLE 11
Number of initiatives to develop GMOs with multiple resistances

Trait	Region																													
	Africa					Asia					Eastern Europe					Latin America					Near East					Total				
	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N
Herbicide and insect	-	2	-	-	1	-	-	-	-	-	-	-	-	-	-	1	8	-	-	3	-	-	-	-	-	1	10	-	-	4
Herbicide and pathogen	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	2	-	-	-	-	-	-	2	-	-	2
Pathogen and stress	-	-	-	-	-	-	-	1	-	1	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-	-	1	-	1
Pathogen and pathogen	-	-	-	-	-	-	2	1	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	1	-	2
Other	-	1	-	-	1	-	1	2	-	3	-	-	-	-	-	-	1	-	-	1	-	-	-	-	-	-	3	-	-	5
Total	-	3	-	-	1	-	3	2	-	3	-	-	-	-	-	1	11	-	-	3	-	-	-	-	-	1	17	2	-	7

C: number of GM varieties released as commercial varieties; F: number of GM varieties in field trials; E: number of activities at experimental level (including laboratory or glasshouse activities); U: number of GM varieties at unknown status; N: number of involved countries. (Totals of this column have been calculated taking into account that sometimes more than one activity is being carried out by the same country, although that country will only be counted once.)

Philippines. In the latter, mango is also being researched, as is tobacco for delayed leaf senescence. Other growth phase changes receiving attention are short-stature and profuse tillering in basmati rice in Pakistan. In Eastern Europe, laboratory work in this area is ongoing in Bosnia and Herzegovina in potato for higher cytokinin levels.

4.5 'STACKING' TRANSGENES – GENERATING CROP VARIETIES WITH MULTIPLE TRANSGENIC TRAITS

The first generation of commercially available transgenic crop varieties has typically included cases where one transgene has been used to add an enhanced characteristic to a particular crop variety. Yet, there are a multitude of characteristics which are assessed by farmers to determine whether a variety is suitable or unsuitable. The production of crops with multiple genetically engineered traits may seem a logical step to follow and, as more locally adapted transgenic varieties become available and accepted on the market, these will become the source material into which novel genes will be incorporated. However, some problems (e.g. trait silencing due to similarities between transgene cassettes or epistatic interactions between transgenes) can arise if too many transgenes are incorporated into a single variety, and such effects may be cumulative over successive generations. To overcome such problems, novel approaches to simplify and improve the process of introducing multiple transgenes into crop varieties are under development.

Where data on the use of multiple transgenes to develop single crop varieties are present in the FAO-BioDeC, the most commonly used dual-transgene combination is herbicide resistance combined with insect resistance (see Table 11).

In Latin America, Argentina has released transgenic maize with *Lepidoptera* resistance and glufosinate tolerance and there are 11 field trials reported in the region on GM crops. The absence of laboratory work suggests that this material is a technology import. Transgenic traits of *Lepidoptera* resistance with glyphosate tolerance are undergoing field trials in alfalfa, maize, soybean and sunflower in Argentina, and in cotton in Argentina, Brazil and Mexico, where maize with *Coloeptera*, *Lepidoptera* resistance and glyphosate tolerance is also being field tested. *Lepidoptera* resistance combined with glufosinate tolerance is undergoing field testing in maize in Argentina. In South Africa, two field trials tested insect resistance combined with bromoxynil or glyphosate tolerance, and maize with potential insect resistance and glyphosate tolerance was field tested. Other traits that are combined with herbicide tolerance are fungal resistance with glufosinate tolerance in wheat in Argentina, and unspecified pathogen resistance with glyphosate tolerance in Mexico. In Argentina, *Coleoptera* and PVY resistant potato is undergoing field trials.

In Asia, two field trials are ongoing in China to test transgenic rice for combined blight and RDV resistance and combined bacterial wilt and PVY resistance in potato, as well as salt and herbicide tolerance in potato. In the Philippines, experiments to combine fungal, insect and bacterial resistance with salt tolerance in rice are underway. Papaya is receiving attention for combined ringspot virus resistance and delayed ripening in the Philippines, and similar work to combine virus resistance with extended shelf life is reported in Malaysia.

Golden rice is a multi-trait transgenic plant since it was made by the transfer of three different transgenes for the synthesis of β-carotene taken from daffodil (*Narcissus pseudonarcissus*) and bacterium *Erwinia uredovora* (Ye *et al*., 2000; Beyer *et al*., 2002). Metabolic pathway engineering is technically complex and challenging, and according to the FAO-BioDeC it has not yet been carried out in any crop within a developing country setting.

5. Conclusions

Even if still largely incomplete, the current data in the FAO-BioDeC allows some general conclusions to be made regarding the state of plant biotechnology research and development in developing countries. It is clear that major differences exist between regions (and within regions) regarding the application of biotechnologies particularly, but not only, in relation to research or development of transgenic crop varieties (Table 12).

The nature of the data sought and obtained by the initial FAO survey makes it difficult to dissect the relationship between transgenic research underway in each country and field trials of transgenic varieties underway in each country. In many instances, it is highly likely that the transgenic varieties under field trial (or commercially released) were developed outside of the country in advanced biotechnology laboratories and do not necessarily indicate that the country has any meaningful research capacity in transgenic crop research. A summary of the transgenic varieties reported to be released is presented in Table 13.

Even in cases where the transgenic variety has been developed in the country (e.g. for a locally adapted variety), it is still often likely that the transgene cassette and transformation protocols for the development of the transgenic variety were developed elsewhere. However, it should be borne in mind that such transboundary technology transfer is cost-effective and allows countries to bypass the risky and costly laboratory stages of research.

In relation to the traits introduced in the transgenic crop varieties, they include resistance to pathogens and pests, herbicide tolerance, abiotic stress tolerance, or modifications to quality traits. Table 12 and shows that 168 (35 percent) of the 479 total GM activities undertaken were for transgenic crops resistant to some pathogen, followed by those resistant to some pest, 97 activities (20 percent) and by those showing modification to some quality traits, 78 activities (16 percent), or resistance to some herbicide, 76 activities (~16 percent). Far less numerous, 40 activities (8 percent of the total GMOs) were transgenic varieties resistant to abiotic stresses and 20 activities (4 percent) being GMOs with multiple resistances. These figures obviously reflect the early stages of such transgenic research.

When experimental stage and field testing stage activities are looked at together (including activities whose stage of development are unspecified), the figures and trends change substantially (Figure 1). While pathogen resistance gathers the highest number of research activities (166), there is a substantial number of research activities towards improved quality traits (76 activities), such as vitamin content, oil composition, delayed ripening, or higher yield, particularly in Asia (34 activities) and Latin America (31 activities). This is reflecting the high interest

TABLE 12

Summary by region of number of initiatives to develop GMOs

Modification	Region																													
	Africa					Asia					Eastern Europe					Latin America					Near East					Total				
	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N	C	F	E	U	N
Pathogen resistance	-	3	4	-	3	2	19	35	14	9	-	-	4	-	1	-	25	51	-	9	-	9	2	-	3	2	56	96	14	25
Pest resistance	2	1	3	-	3	3	16	17	14	7	-	-	-	-	-	1	20	15	-	10	-	2	3	-	2	6	39	38	14	22
Stress resistance	-	-	2	-	2	-	5	7	6	6	-	-	3	-	1	-	1	9	-	5	-	1	6	-	1	-	7	27	6	15
Herbicide resistance	-	11	1	-	1	-	5	-	6	4	1	1	1	-	2	4	34	11	-	7	-	-	1	-	1	5	51	14	6	15
Multiple resistance	-	3	-	-	1	-	3	2	-	3	-	-	-	-	-	1	11	-	-	3	-	-	-	-	-	1	17	2	-	7
Quality traits	-	-	-	-	-	2	3	27	4	8	-	-	10	-	5	-	19	12	-	8	-	-	1	-	1	2	22	50	4	22
Total	2	18	10	-	3	7	51	88	44	10	1	1	18	-	7	6	110	98	-	11	-	12	13	-	4	16	192	227	44	35

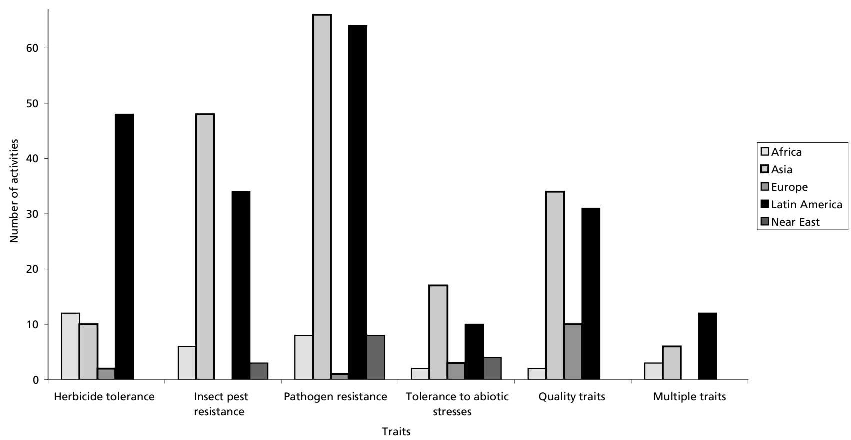
C: number of GM varieties released as commercial varieties; F: number of GM varieties in field trials; E: number of activities at experimental level (including laboratory or glasshouse activities); U: number of GM varieties at unknown status; N: number of involved countries. (Totals of this column have been calculated taking into account that sometimes more than one activity is being carried out by the same country, although that country will only be counted once.)

TABLE 13
GMOs reported as released varieties

Plant species	Character	Country
Cotton	Resistance to *Lepidoptera*	Indonesia
Cotton [1]	Resistance to *Lepidoptera*	China
Cotton [2]	Resistance to *Lepidoptera*	South Africa
Cotton [3]	Resistance to *Lepidoptera*	China
Green pepper [1]	Virus resistance	China
Maize	Not specified	Bulgaria
Maize [2]	Resistance to *Lepidoptera*	South Africa
Maize [2]	Resistance to *Lepidoptera*	Argentina
Maize [2]	Insect and herbicide resistance (Bt)	Argentina
Maize [2]	Resistance to glufosinate	Argentina
Petunia	Altered flower colour	China
Soybean [2]	Resistance to glyphosate	Uruguay
Soybean [3]	Resistance to glyphosate	Argentina
Tomato [1]	Virus resistance	China
Tomato [2]	Delayed fruit ripening	China, the Philippines

1. Cases where the gene for resistance was identified in the country that released the variety and the modified varieties were developed locally.
2. Imported varieties.
3. Cases where the gene for resistance was imported, then crossed to local genotypes

FIGURE 1
Regional GM crop research activities on different traits



of the public sector research in this promising area. Herbicide resistance (71 activities) ranks at nearly the same level as research in quality traits

As may be expected for a trait commercialized by the private sector, the number of field testing activities for herbicide resistance (51) is far in excess of the research initiatives taking place (14). This may simply reflect the fact that the research phase (i.e. development of the herbicide and herbicide tolerant transgene) was conducted at a few locations worldwide and then the technology was distributed already

TABLE 14
Summary by region of number of initiatives to develop techniques in plant biotechnology

Technique	Region																												
	Africa					Asia					Eastern Europe					Latin America					Near East					Total				
	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N	C	T	E	U	N
Plant propagation	15	1	117	2	21	18	9	92	64	10	1	21	96	2	9	16	126	52	2	9	9	1	19	-	8	59	158	376	70	57
Microbial techniques	1	-	22	6	12	-	-	20	6	7	10	10	11	-	5	1	17	17	-	6	-	-	3	-	2	12	27	73	12	30
Molecular markers	-	-	35	-	12	-	-	33	28	9	-	14	30	-	7	2	93	165	-	9	-	-	45	-	6	2	107	308	28	43
Diagnostics	-	-	28	2	10	-	-	7	4	7	1	3	21	-	6	-	17	23	1	7	-	-	12	-	6	1	20	91	7	36
Total	16	1	202	10	21	18	9	152	102	10	12	48	158	2	10	19	253	257	3	9	9	1	79	-	9	74	312	848	117	59

C: technology used on a routine basis and products available on the market; T: results being tested; E: number of activities at experimental level (including laboratory or glasshouse activities); U: activities in unknown phase; N: number of countries involved. (Totals of this column have been calculated taking into account that sometimes more than one activity is being carried out by the same country, although that country will only be counted once.)

incorporated into crop varieties/seeds (either locally or broadly adapted). This is reflected by the relatively high number of herbicide tolerant transgenic crop varieties already available on some markets. The investment of public funds in an area such as herbicide tolerance that is well covered by private investment might not be justified, except in cases where the need for herbicide tolerant crops will not be met by the private sector (e.g. the case for the development of *Striga*-tolerant maize in Africa). The commercially released GM crops are not only limited in their traits, they are also restricted in their diversity, almost all being commodity crops, (See Table 13). However, the FAO-BioDeC has documented a number of research activities being carried out on a wider range of crops (e.g. banana, cassava, cowpea, plantain, rice and sorghum) and traits (abiotic stress tolerance and quality traits) relevant for food security.

According to the FAO-BioDeC, no work is reported as having taken place in the field of nematode resistance in any of the five regions, in spite of the relative importance of the losses caused by nematodes. Another so far scarcely addressed but fundamental problem is the control of post-harvest losses. It is well known that about one-third of the agricultural production in less developed countries is lost due to post-harvest losses. The construction of transgenic varieties characterized by delayed ripening through the block of ethylene production may result also in increased resistance to bacterial and fungal spoilage organisms. While some Latin American and Asian countries are already devoting research efforts to this area, the FAO-BioDeC suggests that African countries are not yet including this area in their research objectives.

In many instances, the lack of national legal frameworks on biosafety (either regulating transboundary movement of transgenics or of field testing requirements[1]), seems to be delaying the testing of transgenic crops and their dissemination to farmers. This applies to both transgenic varieties either developed nationally or imported from other countries. The establishment of appropriate regulatory frameworks for transgenic biotechnology is currently one decisive factor for the regulation of trade of transgenic biotechnology products. This issue will require careful consideration by countries in the context of their long-term plans regarding both food security and competitiveness in international agricultural markets. Such issues should certainly be considered in any countries where public (or private) investment in agricultural biotechnology has been identified as a priority in national agricultural research agendas.

Other factors limiting the rapid adoption of GMOs in developing countries are the lack of appropriate mechanisms for technology transfer as well as the high complexity and costs of the currently elaborated GMO regulating systems; lack of appropriate intellectual property rights (IPR) protection; and weak national plant

[1] One of the major components of the FAO-BioDeC is the section on "Developing Country Biotechnology Profiles", having the objective to provide a platform on which developing country biotechnology related policies, regulations and activities can be readily accessed. All developing FAO member countries are covered and only a few have biotechnology regulatory frameworks in place.

breeding programmes and seed systems. These combine to limit applications only for GM products with large commercial markets (FAO, 2004b).

Other non-GM biotechnologies, particularly those towards plant propagation and molecular markers, are widely applied in the five regions. The numbers are reduced when the use of diagnostic and microbial techniques were looked at (Table14). The uptake of molecular marker technologies does not reflect their potential, however, with over 400 crop/technique combinations being researched or tested, there should be a marked increase in utilization in the near future, with the possibility of improved efficiency in plant breeding and germplasm characterization. In general, efforts could be enhanced in all areas, as the application of low-cost genetic marker techniques could significantly improve progress in plant breeding.

Many of the plant cell- and tissue-culture technologies have been readily available for many years, and have been taken up where appropriate, such as in microprogagation of vegetatively propagated crops, for example, banana and date palm. Given the necessary R&D costs, expectation of success can be good, as many crops previously considered recalcitrant are now commercial successes, either as a means of propagation of elite stocks, or as a source of virus free material. Input into *in vitro* regeneration may be expected to increase, as it is a prerequisite for many of the technologies. It should be borne in mind that labour costs are a major determining factor for the commercial viability of many micropropagation and tissue-culture enterprises, especially those developing products for export markets.

However, the uptake of micropropagation techniques for *in vitro* germplasm conservation is low. This may be attributed to the existence of established whole plant germplasm collections for species where *in vitro* conservation is appropriate, leading to reluctance to provide funding for *in vitro* facilities. The balance between *in vitro* and whole plant collections may change as facilities for, and capabilities in, *in vitro* conservation increase and existing plant collections need rejuvenation.

The suspected under-reporting of cell biology, diagnostics, molecular marker and food processing techniques may be due to the fact that they are routinely used in some countries. As a result, some informants did not consider them to be ‘high tech’ biotechnologies to be documented in the FAO-BioDeC, or it may be a reflection of a lack of knowledge by some respondents of the extent of their use in agricultural sectors. Future surveys should strive to bring out as much detail as possible on these relatively affordable and less controversial biotechnologies.

Microbial techniques (e.g. Bt) for the control of pests and pathogens may represent an effective alternative to genetic transformation for resistance to pests and diseases. While it may be initially perceived that biocontrol agents can enjoy broader public acceptance than transgenic crops, this may depend on the scale of use of such agents, their channels of distribution (public versus private sector), whether they are related to any microbes causing human disease, and what the environmental effects would be of large scale application of microbial control agents in agriculture. At present, differing risk assessment procedures are applied to Bt delivered within transgenic plants than to Bt delivered as a pesticide (e.g within organic production). In theory, however, many microbial control agents could allow the avoidance of the presence of chemical residues from conventional pesticides on horticultural crops and on fruits for fresh/immediate consumption.

Nitrogen-fixation has long been a desired yet elusive ‘green’ biotechnology. However, the objective of improving the plant-*Rhizobium* symbiosis or other associations is not easy to achieve, due to the complexity of the relationships, the multiplicity of factors involved, the specificity of the interaction between the two organisms, the influence of the environment on the system expression and the possible competition between beneficial and other soil microflora. In the near future, the resources needed for achieving biological nitrogen fixation in non-legumes will be competing with the wide range of biotechnological approaches that have a greater chance of achieving results in a shorter time frame, such as development of crop plants with enhanced nitrogen use efficiency or nitrogen fixation tolerance to water deficits. However, the use of model crop legumes such as *Medicago truncatula* and *Lotus japonicus* in combination with high-throughput genomics research will lead to an elucidation of the genetic basis of nitrogen fixation in legume symbionts, and allow decisions to be made regarding the transfer of nitrogen fixation capacity to non-leguminous crops.

The use of microorganisms to change food characteristics by fermentation to produce bread and beer has been an established technology for thousands of years, but microorganisms are also widely used in other commercial food processing and enzyme production, farm scale or domestic processes, mostly using agricultural or plant products as the starting point. The ability to modify microbial genomes has expanded the range of products that can be produced, and enabled modification of a wider range of agricultural products. Future developments of this technology will go hand in hand with the ability to engineer plants to produce chemicals, or modified food products, reducing the need for separate subsequent microbial processing.

From the FAO-BioDeC, it can be concluded that countries like Argentina, Brazil, China, Cuba, Egypt, India, Mexico and South Africa now have well developed agricultural biotechnology programmes in both NARS and in the academic sector. These countries are now approaching the leading edge of biotechnology applications and have significant research capacity. For instance, a Chinese research team has now sequenced the entire rice genome in a matter of months; a task that would have been considered unachievable by most countries a few years ago. In addition it shows that a range of countries including Bangladesh, Indonesia, Malaysia, the Philippines and Thailand in Asia; Cameroon, Kenya, Morocco, Nigeria, Tunisia and Zimbabwe in Africa, and Chile, Colombia, Costa Rica, Ecuador and Venezuela, in Latin America, now have medium-scale biotechnology programmes usually in a few key areas.

5.1 CHALLENGES FOR BIOTECHNOLOGY APPLICATION IN DEVELOPING COUNTRIES

Biotechnology could support solving many of the constraints that limit crop, livestock, forestry and fishery production. However, national programmes need to ensure that all sectors, including resource-poor rural populations in marginal areas where productivity increases are difficult to achieve, benefit from biotechnology.

Certain biotechnology require high investments and should therefore complement existing technologies, be demand-driven, and used only when it offers a comparative advantage. Priority setting should involve multiple stakeholders and take into account national development policies, private sector interests and market opportunities.

Since much biotechnology research is conducted by private companies in industrialized countries, appropriate models for intellectual property rights legislation are critical for access to the results of biotechnology research originating elsewhere. Equitable partnerships between foreign and local institutions can help to acquire know-how and yet soften the patent requirements. Legislation is also needed to regulate activities e.g. specifications for introduced genetic material, animals and plants. Developing countries may need assistance in developing appropriate legislation and setting up regulatory bodies for biosafety. Legislation developed must be consistent with evolving international policy agreements and reflect national positions and needs.

It is imperative that developing countries are not left at the edge of development nor in a disadvantaged position. For this, capacity building initiatives are needed, including policy development, institutional strengthening and human capacities putting into place incentives for adequate and sustained funding and regulatory framework development.

FAO, together with other partners, is ready to help member countries to optimize their capacity to develop, adapt and use biotechnology and its products to meet their needs, to enhance food security and improve living standards, while minimizing possible risks and negative impacts.

References

Beachy, R.N. 1999. Coat-protein-mediated resistance to tobacco mosaic virus: discovery, mechanisms and exploitation. *Phil. Trans. Roy. Soc. of Lond. Series B-Biol. Sci.,* 354, 659–664.

Bebawi, F.F. & Farah, A.F. 1981. Effect of parasitic and non-parasitic weed on sorghum. *Experimental Agriculture,* 17: 337–341.

Beyer, P., Al-Babili, S., Ye, X., Lucca, P., Schaub, P., Welsch, R. & Potrykus, I. 2002. Golden Rice: introducing the carotene biosynthetic pathway into rice endosperm by genetic engineering to defeat vitamin A deficiency. *J. Nutrition,* 132: 506S–510S.

Boyer, J.S. 1982. Plant productivity and the environment. *Science,* 218: 443–448.

Brink, J.A., Woodward, B.R. & DaSilva, E.J. 1998. Plant biotechnology: a tool for development in Africa. *EJB Electronic Journal of Biotechnology,* 1 (3): 1–10.

CBD. 1992. What is biotechnology? Available at http://www.biodiv.org/biosafety/faqs.asp?area=biotechnology&faq=1.

COAG. 1999. Biotechnology. FAO Committee on Agriculture, 15th Session, 25–29 January 1999. Available at http://www.fao.org/unfao/bodies/coag/Coag15/X0074E.htm.

Ejeta, G., Butler, L.G. & Babiker, A.G.T. 1992. *New approaches to the control of Striga*. Striga research at Purdue University. Bulletin RB-991, Agricultural Experimental Research Station. West Lafayete, Indiana, Purdue University, USA. 27 pp.

El-Nawawy, A., Barakat, S., Elwalily, T., Abdel-Moneim Deghady, A. & Hussein, M. 2002. Evaluation of erythropoiesis in protein energy malnutrition. *Eastern Mediterranean Health Journal*, 8–2&3. Available at http://www.emro.who.int/publications/emhj/0802_3/evaluation.htm.

FAO. 2001 *Glossary of biotechnology for food and agriculture.* Available as tri-language searchable database at http://www.fao.org/biotech/index_glossary.asp.

FAO. 2003. *Molecular marker-assisted selection as a potential tool for genetic improvement of crops, forest trees, livestock and fish in developing countries.* Background document to conference 10 of the FAO Biotechnology Forum. Available at http://www.fao.org/biotech/C10doc.htm.

FAO. 2004a. *Biotechnology applications in food processing: can developing countries benefit?* Background document to conference 11 of the FAO Biotechnology Forum. Available at http://www.fao.org/biotech/C11doc.htm.

FAO. 2004b. *The State of Food and Agriculture: Agricultural Biotechnology: Meeting the needs of the poor?* Available at http://www.fao.org/DOCREP/006/Y5160E/Y5160E00.HTM.

IAC (InterAcademy Council). 2004. Realizing the promise and potential of African Agriculture. Available at http://www.interacademycouncil.net/report.asp?id=6959.

Lagoke, S.T.O., Parkinson, V. & Agunbiade, R.M. 1991. Parasitic weeds and control methods in Africa. *In* S.K. Kim, ed. *Combating Striga in Africa*. Proc. of the Int. Workshop. Organized by IITA, ICRISAT and IDRC, 22–24 August 1988, IITA, Ibadan, Nigeria. 3-14.

Nester, E.W., Thomashow, L.S., Metz, M. & Gordon, M. 2002. 100 years of *Bacillus thuringiensis*: A critical scientific assessment. Washington, DC, American Academy of Microbiology. Available at http://www.asm.org/Academy/index.asp?bid=2129.

Oerke, E.C., Dehne, H.W., Schonbeck, F. & Weber, A. 1994. *Crop production and crop protection: Estimated losses in major food and cash crops*. Amsterdam, Elsevier.

Pennisi, E. 2001. The push to pit genomics against fungal pathogens. *Science,* 292: 2273-2274.

Ribant, J.M., Banziger, M. & Hoisington, D. 2002. *Genetic dissection and plant improvement under abiotic stress conditions: drought tolerance in maize as an example*. JIRCAS Working Report (2002) 85-92. Available at http://ss.jircas.affrc.go.jp/kanko/Working%20Report/No23/10.pdf.

Sasser, J.N. & Freckman, D.W. 1987. A world perspective on nematology; the role of society. *In* J.A. Veech & D.W. Dickerson, *Vistas on nematology*, pp. 7–14. Hyattsville, USA, Society of Nematologists.

Tabashnik, B.E. 1994. Evolution of resistance to *Bacillus thuringiensis*. *Ann. Rev. Entomol.,* 39: 47–79.

World Hunger Facts. 2004. Available at http://www.worldhunger.org/articles/Learn/world%20hunger%20facts%202002.htm.

Ye, X., Al-Babili, S., Klöti, A., Zhang, J., Lucca, P., Beyer, P. & Potrykus, I. 2000. Engineering provitamin A (-carotene) biosynthetic pathway into (carotenoid-free) rice endosperm. *Science*, 287: 303–305.

APPENDIX 1

List of countries by region covered by FAO-BioDeC

Africa
Algeria
Burundi
Cameroon
Chad
Congo Republic
Côte d' Ívoire
Democratic Republic of the Congo
Ethiopia
Gabon
Ghana
Kenya
Madagascar
Malawi
Mali
Nigeria
Rwanda
Senegal
South Africa
Uganda
Zambia
Zimbabwe

Near East
Afghanistan
Egypt
Iran
Islamic Republic of Iran
Jordan
Kuwait
Morocco
Sudan
Syrian Arab Republic
Tunisia
United Arab Emirates

Asia
Bangladesh
China
India
Indonesia
Republic of Korea
Malaysia
Myanmar
Nepal
Pakistan
Philippines
Sri Lanka
Thailand
Viet Nam

Europe
Albania
Armenia
Azerbaijan
Bosnia and Herzgonia
Bulgaria
Croatia
Georgia
The Former Yogoslav Republic of Macedonia
Republic of Moldova
Serbia and Montenegro

Latin America & the Caribbean
Argentina
Bolivia
Brazil
Chile
Colombia
Costa Rica
Cuba
Ecuador
Grenada
Guatemala
Honduras
Mexico
Paraguay
Peru
Uruguay
Venezuela