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Plant Breeding in Preparation for the 21st Century

M S SWAMINATHAN
Member, Planning Commission, Yojana Bhavan New Delhi 110001

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I. Introduction

Knowledge from space exploration suggests that man will continue to depend on the earth for meeting his first hierarchical need—food. Also, in spite of the substantial progress made in capture fisheries the oceans now provide only 2% of the global food intake. Both inland and coastal aquaculture are, however, likely to provide more food in the years ahead. Even then, the soil will continue to be the backbone of agriculture. Land will, however, be a shrinking resource for farming in terms of area, since competing demands for its use for domestic, community and industrial purposes will grow. We will have to learn to face the challenge of having to grow more and more food from less and less land area in the years to come.

Success in agricultural production will depend upon success in generating a symphony approach among all concerned with farming—scientists, farmers, extension workers, input supply agencies and policy makers. Similarly success in the development of economically viable technologies suited for different agro-ecological conditions will depend upon the extent of interdisciplinary scientific effort generated. Although I have chosen plant breeding for examination in relation to the needs of the 21st century, similar exercises will be needed in every branch of agricultural science. I have chosen to discuss the implications of the emerging global agricultural scenario for plant breeders for two reasons—first, my personal scientific experience is in this field, and secondly, a new geno-type usually triggers changes in management practices, in addition to helping to get the best out of a given environment. The release of hybrid maize in the United States in the early nineteen thirties led to the improvement of not only maize production but also of other crops. Farmers who saw the economic benefit of improved soil fertility and plant protection practices in hybrid maize started adopting better management practices in other crops as well. Quantum jumps in production were thereby achieved.

The release of dwarf varieties of wheat and rice in the mid-nineteen-sixties in our country served as catalyst of change in several areas of agricultural development. Success in the Intensive Agricultural District Programme (IADP) initiated in 1961 was limited until genetic strains which could respond to the package of improved practices introduced under IADP, particularly the application of fertiliser and water, were made available under the High-Yielding Varieties Programme in 1966–67.

It may take anywhere from 10 to 15 years from the time a cross is made to the time a new variety makes a significant impact on production. Therefore, it will be prudent to examine the kinds of reorientation our plant breeding programmes may have to be given in order to help the country to achieve a position of primacy in the production of agricultural products in the 21st century. What are the emerging opportunities as well as difficulties which have a bearing on the restructuring of the plant breeders' assembly line? I shall try to deal with this question, in relation to the emerging scenarios in demographic trends, ecology, energy, employment and economics. I shall first describe the implications for the plant breeder of developments in these areas and later refer to the techniques which may be of help in facing the new challenges. In relation to the choice of plant breeding techniques, I would like to reiterate my oft-repeated view "do not worship any particular tool or method; select such techniques and methods which are likely to help in reaching a specific goal speedily and surely".

II. Emerging Scenarios

(a) Population Growth: From the origin of mankind to the end of the 18th century, world population reached only one billion. The second billion followed in little more than a century, between 1800 and 1925. Between 1925 and 1975, the 3rd and 4th billions were added. The fifth and sixth billions are expected by 2000. A disproportionately large share of this increase is taking place in the developing countries including our own. Nine-tenths of the global increase since 1925 occurred in Africa, Latin America, Asia (excluding Japan and the Asiatic part of USSR) and Oceania (excluding Australia and New Zealand). With international migration possibilities getting progressively reduced, each country will have to meet the needs of its population primarily from its own land and water resources.

In India, the decadal growth rate in population according to the 1981 census works out to 25.0% for 1971–1981. The exponential growth rate for the country for the period 1971–1981 works out to 2.23% as compared to 2.20% in the earlier decade. By plotting the census 1971–81 growth rate of population by districts, the Registrar General of India has identified the areas where the decadal population growth rates are above 22.5%. According to such a district-wise analysis, there are 218 districts which need concentrated attention. Seventy-one of these 218 districts need even greater attention since population growth rate in them exceeds 3% per annum. Since the trend in the decline of death rates (table 1) is likely to continue, the Science Advisory Committee to Cabinet has suggested the organisation of a Human Resource Planning and Development Group in every Block to promote an appropriate strategy in the block for achieving population stabilisation.

Population projections made in the Planning Commission, using two different alternatives (i.e. NRR = 1 by 1996 or

Table 1 *Birth and death rates/1000 persons in India*

Period	Birth rate	Death rate
1931-1941	45.2	31.2
1941–1951	39.9	27.4
1951–1961	40.9	22.0
1961–1971	41.2	19.0
1971–1981	37.1	14.8

2010) show that in 50 years from now we may have a population of about 1231 or 1375 million (table 2). If the programmes now planned for improving female literacy, economic emancipation of women and for widespread voluntary adoption of the small family norm succeed, it should be possible to contain the population size at 1231 million in AD 2030–31. We will then need to produce 277 million tonnes of food grains to meet a per capita requirement of 225 kg per year.

Table 2 *Estimated population of India (Projections of the Perspective Planning Division of the Commission)*

Year	Assumption[1]	Population (Million)	Dependency Ratio[2]
1981	—	683.8	0.84
2001	A	940.3	0.58
,,	B	1003.1	0.67
2031	A	1231.7	0 57
,,	B	1375.4	0.56

[1]Assumption A: NRR= in 1966
,, B: NRR= in 2010
[2]Dependency ratio: $\frac{(0\text{–}14+60^{+})}{15\text{–}59}$

The age structure of our population is such that large numbers of young people will need opportunities for gainful employment. Currently we are a nation consisting predominantly of young persons but the dependency ratio will gradually decline (table 2). In other words, we should strive to avoid not only famines of food, but also famines of work. Without work the purchasing power needed for buying food will not exist. Being a large country, we should also be prepared for local disasters arising from natural calamities. Plant breeders will have to place equal emphasis on selection criteria designed to identify geno-types which will help to elevate and stabilise food production and generate opportunities for gainful employment.

(b) Ecology: Among the problems which are likely to assume significance in the future are:

(i) growing desertification leading to a destruction or diminution of the biological potential of land and water because of denudation of forests, soil erosion, unscientific irrigation and different kinds of pollution;
(ii) gene erosion due to monoculture and habitat destruction; and
(iii) climate changes arising from the burning of fossil fuels.

Desertification can be contained through appropriate measures of afforestation, control of soil erosion and scientific land use. Steps have been taken through agencies like the International Board for Plant Genetic Resources and the National Bureau of Plant Genetic Resources which can help to preserve for posterity the fruits of thousands of years of natural and human selection. Bhag Singh (1981) has described in detail how the *Citrus* wealth of Meghalaya is proposed to be preserved through a gene sanctuary.

By the middle of the next century, the continued burning of fossil fuels as a source of energy is likely to result in a doubling of CO_2 content in the atmosphere relative to the amount present in 1860. The present CO_2 level of about 335 parts per million per volume (ppm) is expected to increase to about 380 ppm by the end of the century (Bach 1981). Such an increase will have two kinds of consequences: an effect on photosynthesis because of the greater quantity of carbon available to plants from the atmosphere and changes in climate. Computer models indicate that on a global basis, average temperatures upon the earth's surface will rise between 2°C and 3°C with a doubling of atmospheric CO_2. Both evaporation and precipitation may increase by about 9%.

Given adequate solar radiation, soil nutrient availability and irrigation, increased atmospheric CO_2 should act as a fertiliser for crop plants raising both photosynthetic production and water-use efficiency. Greenhouse experiments have indicated that a doubling of CO_2 under good crop management can increase biomass yields by about 4%. Structural adaptations in farming systems will be necessary both to take advantage of the favourable consequences of CO_2 increase and to face its negative repercussions. The CO_2 effects should be especially important for crop plants such as rice, wheat, millets and potatoes which have a C_3 photosynthetic pathway. Corn, sugarcane and sorghum, with a C_4 pathway, are likely to be limited by solar radiation and nutrient and moisture availability rather than by CO_2.

Plant breeders in India should aim at development of varieties that will have higher net photosynthetic production and use less water as the atmospheric CO_2 content increases. The strains should not, however, respond to a warmer atmospheric temperature by an increase in respiration that would cancel out the effect of CO_2 fertilization. There is an opportunity for pushing forward with attempts to increase total phytomass production in the major crop plants.

Herman Flohn (1981) has recently estimated the changes in average surface temperature and precipitation that may occur in different latitude belts if atmospheric CO_2 goes up to 560–580 ppm (i.e., about twice the 19th century value).

Latitude	Average annual change in surface temp. (°C)	Change in precipitation
60°N	+7.5°	+ 18%
50°N	6°	+ 4%
40°N	+6°	−14%
30°N	+4.5°	0%
20°N	+2.5°	+ 20%
10°N	+1.5°	+ 20%
Equator	+3°	0%
10°S	+4°	— 20%
20°S	+4.5°	— 5%
30°S	+4°	+ 5%
40°S	+4°	+ 12%
50°S	+3°	+ 12%
60°S	+2.5°	+ 12%

If Flohn's estimates prove correct, major changes in surface and underground water supply could occur due to altered precipitation and evapo-transpiration patterns in several parts of the world. Some of the agriculturally productive areas of USA, Canada and USSR may be adversely affected. USA, USSR and China have about 90% of the world's coal reserves. Since higher CO_2 concentrations may affect these countries adversely, they may be unwilling to develop an export trade in coal and this, in turn, will have implications for the energy-short countries (Revelle 1981).

As far as India is concerned, the kinds of projections made by Herman Flohn would imply more rain in some of the drought prone areas and more floods along the Ganga and Brahmaputra. Expansion in major and medium irrigation works as well as extensive denudation of vegetation may also influence weather, particularly the micro-climate, in different ways. Hence, the plant breeder with the help of climatologists and environmentalists will have to assemble diverse genotypes which will profit from increased CO_2 and precipitation or alternatively, withstand the adverse impact of higher temperature and enhanced evapo-transpiration.

Anticipatory breeding in this area will include steps for:

(i) developing strains which can help to enhance productivity per day and per litre of water;

(ii) breeding of varieties which can help to tap the production potential of flood-free seasons in flood prone areas;

(iii) taking advantage of opportunities for external trade that may emerge in case the traditional "breed basket" areas of the world find it difficult to sustain production at high levels;

(iv) developing genotypes which can derive advantage from enhanced CO_2 availability; and

(v) conserving genetic variability and maintenance of genetic diversity in crop populations.

(c) Energy requirements: Southern and Eastern Asia have 50% of the world's population and only 16.5% of the world's total energy resources. If China is excluded, the position will be 30% of the world population versus 3.2% of estimated total energy resources. If we accept that the only option open to us in agriculture is working for increased productivity and expansion of productive land through a higher cropping intensity and through a better planning of the use of cubic volumes of soil and air by companion cropping, then the energy requirements of this pathway of agricultural growth will have to be worked out. At present, agriculture which helps to produce about 40% of India's national income and provides jobs to over 70% of the population, consumes only 10% of the commercial forms of energy (table 3). Modern agriculture demands increasing quantities of energy in order to achieve the desired levels of productivity. The efficiency of energy use can be much higher under small farm and labour-intensive systems of agriculture as compared to the large, mechanised "super-farm" operations (table 4).

Table 3* *Relative shares (%) of different forms of commercial energy for various sectors in 1978–79*

Sector	Energy from			Percentage of total commercial energy consumption
	Coal	Oil	Electricity	
Household	10.0	71.2	18.8	13.7
Agriculture	0.0	61.8	38.2	10.6
Industry	44.5	7.9	46.6	38.5
Transport	13.3	83.9	2.8	31.7
Others	11.9	36.2	51.9	5.5

**Source:* *Report of the Working Group of Energy Policy, Planning Commission, 1979*

Table 4 *Diesel (equivalent) consumption per tonne of grain production*

Crop	India		US	
	Yield	Litres t^{-1}	Yield	Litres t^{-1}
Maize	2.5	50	5.4	306
Wheat	4.0	21	2.0	102
Rice	7.0	93	6.1	170

(Data of Professor S K Sinha)

The energy required to produce 3 tonnes of food grains on a gross-cultivated hectare would be about 38% of the food energy of the crop. This is equivalent to 4 million Kcal or to 0.36 tonnes of petroleum-based fuel. About half of the fuel requirements now go to producing the fertilizers essential for increased production.

Thus, the most serious resource deficiency likely to diminish the prospects for bridging the gap between potential and actual farm yields will be energy. Apart from steps such as enhanced efficiency in energy conservation and use and improved biological N_2 fixation, the following are the other possible measures:

(i) Find undiscovered fuel resources;
(ii) Fully exploit renewable energy resources like biogas and biomass and hydel and wind power;
(iii) Step up R & D efforts in solar energy harvest and utilisation; and
(iv) Develop nuclear power as a major source of energy.

In India it will not be easy to find land for projects such as the extraction of ethanol from sugarcane. To produce 1 million barrels a day of oil equivalent, which is equal to 1% of the world's total consumption of energy in all forms, we will need twice the total area now under sugarcane in the world. Social forestry and biomass production programmes particularly in degraded and waste lands coupled with pyrolysis offer greater prospects in India. This will, however, need extensive community participation. While success in biomass production and utilisation will depend greatly on efforts in social engineering under conditions of individual ownership of land, nuclear power generation is independent of this requirement. Nuclear power generation has thus an added advantage in countries with a growing pressure of population on land. We need detailed planning of energy production and distribution for the agricultural sector. Otherwise, the potential of this sector for providing more jobs and income, in addition to food, will never be realised. Plant breeders should include the efficiency of conversion of cultural energy into food energy as one of the indices of selection. Also, the breeding for greater per day dry matter production in fuel and fodder shrubs and trees needs intensive attention.

(d) Economics: The poverty trap in which a majority of our rural people find themselves in is an example of a feedback loop. Increased population size is leading to a reduction in the average size of an operational holding (table 5). Since

Table 5 *Land holdings in India*

Size	No. of holdings			
	In million		In percentage	
	1970–71	1976–77	1970–71	1976–77
Marginal *(Below 1 ha)*	36.20	44.53	50.9	54.6
Small *(Between 1–2 ha)*	13.43	14.70	18.9	18.0
Semi-Medium *(Between 2–4 ha)*	10.68	11.64	15.0	14.3
Medium *(Between 4–10 ha)*	7.93	8.21	11.2	10.1
Large *(10 ha and above)*	2.77	2.44	4.0	3.0

a majority of small and marginal farmers generate little surplus, they cannot generate capital for being invested to enhance the productivity of land and livestock. High interest rates further enhance the unattractive nature of investments in land and water based occupations. As mentioned earlier, 98% of global food supply is land dependent, the oceans providing only the remaining 2%. The dilemma of finding large additional financial resources for elevating and stabilising agricultural productivity in the midst of an unfavourable environment for investment in rural professions has to be resolved soon.

In many parts of the country where land availability is a principal constraint, the numbers of landless labour and marginal farmers are high. Their numbers will rise further under the impact of continued population growth and the consequent fragmentation of small holdings. In all cases, the result will be a movement of population, especially young people, towards the town and a continual increase in the number of urban unemployed. The new wave of technological change spear-headed by automation and computerization has dethroned labour from its traditional position as the dominant factor of production in the developed countries. A large human resource under such conditions tends to become a liability and leisure time planning assumes as much importance as work planning. Such a pathway of economic growth will obviously lead to a great human misery in our country. The pathway which can help us to derive benefit from our human population is one which can foster the linking of this resource with sunlight through the medium of green plants. A "photosynthetic pathway" of development will call for steps designed to increase the productivity of small farms, to maximise employment in rural areas for the landless and to guarantee minimum nutrition standards for both the urban and rural poor. A transportation network is essential both for delivery of inputs and marketing of produce.

The problems of landless labourers and the urban poor are particularly difficult, and no standard solution exists. Some calculations indicate that acquisition and redistribution of 5% of total land among landless labour would reduce poverty levels in India by 30% (Nurul Islam 1981). Our large programme in the field of irrigation should help to find extra land for redistribution. A clear understanding of the quantitative and qualitative dimensions of the problem is, however, essential for the development of public policies which will help to promote the desired degree of diversification of opportunities for gainful employment. In particular, a detailed analysis of trade scenarios with respect to home as well as external trade will be necessary to decide on optimum land and water use patterns. The photosynthetic model of development will require detailed block level analysis of both input requirements and output potential. Employment impact analysis will have to become an integral part of investment decisions. Employment opportunities for rural women should receive explicit recognition in technology development. The production of F_1 seeds in cotton through hand emasculation and pollination by rural women is an example of a relevant plant breeding methodology under our conditions.

Producer-oriented marketing is a must for minimising the gap between what the producer gets and the consumer pays. Internationally, a larger potential for increased trade exists in respect of food grains, cotton, vegetable oils, roots, sugar and a wide range of horticultural products. According to FAO calculations, gross imports of cereals of 90 developing countries will be 151 and 333 million tonnes respectively in AD 2000 and AD 2030. Opportunities for trade in food and food-grains will hence grow.

Input-output pricing policies and organisation of small farmers in a manner that can optimise the efficiency of the use of purchased inputs are important to make agriculture an economically viable profession. Fertiliser price in our country is high and fertiliser use efficiency very variable. The cost-risk-return structure of farming influences the decisions of farmers on land and input use. Plant breeders will hence have to measure the ability of the genotype to use purchased inputs efficiently and economically.

III. Tasks Ahead

(a) Enhancing the ceiling to yield: The fore-going account of emerging scenarios in population growth, economics of farming, energy needs and employment generation underlines the urgency of raising the ceiling to yield coupled with enhanced stability of output. The gap between potential and current experimental yields is fortunately still considerable. Productivity advance helps to save area under different crops and thus helps to face problems arising from the diversion of land to alternative uses. For example, Borlaug (personal communication) has calculated that had there been no productivity advance in the United States since 1938–40, 197 million ha more land will be needed to produce the quantity of crops now harvested. In India, we will need about 34 million ha of additional planting to produce the quantities of wheat and rice we now produce, had there been no advance in increasing average yields since 1966–70 (table 6).

The average and record yields obtained in some important crop plants are given in (tables 7 & 8). Obviously, the immediate pay off will come from an accelerated effort in technology transfer. While the small farm offers good potential for intensive agriculture, the small farmer faces many problems because of his inability to face risks and invest on cash inputs. Only by solving the problems of small farmers, can the potential productivity of small farms be realised.

What is the scope for a further improvement in yield potential? Data given in table 9 would indicate that a dry matter production of 670 kg/ha/day or 67 g/m^2/day may be possible. In plants with the C_4-dicarboxylic acid pathway of photosynthesis, rate for top growth somewhat above 50g/m^2/day has been reported.

Table 6 *Impact of improved technology on land requirement*

Crop	Year	Yield (M.T./ha)	Production (1000 M.T.)	Area saved by yield increase (1000 ha)
Rice	1966–70	0.981	35,770	—
”	1979	1.328	53,770	14,331
Wheat	1961–66	0.830	10,950	—
”	1979	1.574	35,510	20,222

Table 7 *Average yield of different crops (1979–80)*

Crop	kg. ha^{-1}
Wheat	1568
Rice	1330
Sorghum	708
Maize	1076
Pearl Millet	445
Barley	1169
Gram	744
Pigeonpea	715
Kharif pulses	273
Rabi pulses	430
Groundnut	835
Rapeseed & Mustard	525

Source: Agricultural Situation in India

Table 8 *Record yield of some crops in experiment stations*

Species	Yield (kg/ha)	Source
Wheat *(Triticum aestivum)*	10,000	BHU
	7,700	All-India Coord. Project on Wheat
Rice-Paddy *(Oryza sativa)*	14,000	AICRIP
	10,000	PAU and All-India Coord. Project
Maize (*Zea mays*)	11,500	All-India Maize Improvement Project
Sorghum (*Sorghum bicolor*)	8,500	All-India Coord. Sorghum Project
Mustard (*Brassica* sp.)	3,800	PAU
Bengal gram-Chickpea (*Cicer arietinum*)	4,500	BHU JNKV, Jabalpur IARI, New Delhi
Arhar-Pigeonpea (*Cajanus cajan*)	3,500	All-India Coord. Project IARI, New Delhi
Sugarcane (*Saccharum officinarum*)	1,41,000	All-India Coord. Res. Project on Sugarcane
Napier grass	500 tonnes ha^{-1} fresh weight	Sewa Ashram, Chitrakoot Nutrient Film Technique

AICRIP = All India Coordinated Rice Improvement Project, Hyderabad
BHU = Banaras Hindu University, Banaras
IARI = Indian Agricultural Research Institute, New Delhi
JNKV = Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur
PAU = Punjab Agricultural University, Ludhiana

If 20% is added for root growth, the value 67 g is nearly reached. Plants with the C_3-Calvin Cycle, a growth rate of 35 g/m^2/day for shoot and root has been recorded.

The higher capacity of the C_4 plants is mainly expressed at high light intensities and temperatures. Under such conditions, water economy is essential. Although short term growth rates for some C_4 grasses approach the yield level of 67.0 tonnes dry matter/ha, most of the yields even in advanced agricultural systems reach only about one third of this potential.

It is often remarked that the yield levels of grain legumes and oilseed crops are low as compared to cereals. While making such comparisons, it should be recognised that 1 g of glucose can make 0.83 g of carbohydrates or alternatively 0.40 g of proteins or 0.33g of lipids. This is why there is often a protein penalty with high calorie yield and vice versa. It is hence important that plant breeders study carefully (a) total dry matter production, (b) partitioning of dry matter between grain and other plant parts, and (c) nitrogen harvest index. Fortunately, there exists scope for making advances in all these areas along desired directions (Sinha & Swaminathan 1981).

(b) Systems approach in selection: In earlier papers (Swaminathan 1978, 1980) I had referred to the need for integrating in plant breeding programmes in the tropics and sub-tropics the following selection criteria:

Table 9 *Calculation of potential productivity by a crop surface (basic data from Moon 1940, Loomis-Williams 1963; Mac Key, 1979)*

Total solar radiation during vegetation period, range	10—80 × 10^9 cal/ha/day
Mean	50 × 10^9 cal/ha/day
Mean of visible radiation (400–700 mμ)	22 × 10^9 cal/ha/day
Total quanta available for photosynthesis	353 × 10^3 Einsteins/ha/day
Equation of photosynthesis: $CO_2 + H_2O + nhv = (CH_2O) + O_2$ Where $n \simeq 10$, h = Planck's constant, v = wave frequency	
Amount of carbohydrate (CH_2O) produced	353 × 10^2mol/ha/day
Gross production of weight (30 g/mole CH_2O)	1,060 kg/ha/day
Respiration loss (33%)	—350 kg/ha/day
Net production (CH_2O) of weight	710 kg/ha/day
Inorganic matter to be added (8%)	+57 kg/ha/day
Reduction due to higher mean caloric content of total plant dry matter than 3.740 cal/g carbohydrate (CH_2O), 10–15%	—97 kg/ha/day
Net dry matter production	670 kg/ha/day (67 g/m^2/day)
Dry matter yield/100 days vegetation period	
Grain yield (12% H_2O) at a grain: straw : root ratio of 5 : 3 : 2	37,500 kg/ha

(1) Population performance so as to get maximum yield per square metre of soil surface in monoculture.
(2) High productivity per unit of time, water and cultural energy.
(3) High photosynthetic ability.
(4) Low photorespiration (where relevant).
(5) Relative insensitivity to photoperiod and temperature (where relevant).
(6) High response to nutrients.
(7) Multiple resistance to pests.
(8) Better nutritive properties.
(9) Better storage and processing properties.
(10) Crop canopies that can retain and fix maximum CO_2.
(11) Ability to cooperate with other companion crops so as to provide in inter-cropping systems maximum yield/cubic volumes of soil and air,
(12) Suitability for different multiple and relay cropping systems as well as for different farming systems, such as crop-livestock, crop-fish, etc.

Stability of performance is as important as high yield potential. This will call for a high degree of resistance to important pests and diseases. Study of variability for root systems is important for improving performance under conditions of inter-cropping and dry farming. Similarly, breeding for "easy care" finishing properties is important in a crop like cotton faced with competition from synthetics. Mac Key (1979) has described some aspects of cereal breeding for reliable and high yields.

As the area under irrigation increases, problems of alkalinity, salinity and water logging may increase. Rana (1977) has described methods of breeding for adaptation to soil alkalinity and salinity.

Suitable screening procedures will have to be developed, depending on the nature of the soil health problem encountered.

(c) Special opportunities in labour intensive agriculture: We have special opportunities arising from our rich human resource which are not available to plant breeders in countries with capital intensive and labour displacing systems of farming. Hybrid cotton like H.4 and Varalakshmi produced by hand emasculation and pollination is a good example of the intelligent use of our special strengths. Some of our private breeders are producing hand-pollinated hybrid seeds of *Petunia* and several other ornamental plants for export. We need to enlarge this area of trade.

We should also explore the possibility of developing hybrids of jute and many shrubs and trees. Raising potato from true seeds and release of hybrids in rice and forest trees are other immediately feasible opportunities. The release of hybrids characterised by heterosis for root growth and early seedling vigour will be of great value in improving yields under unirrigated conditions.

(d) Tailoring duration to suit different seasonal conditions: By integrating information from agro-meteorological studies, strains to suit different weather probabilities will have to be bred. For varieties to be planted during the SW monsoon season at least the following 4 probabilities will have to be kept in view:

(i) Late onset of monsoon;
(ii) Early withdrawal of monsoon;
(iii) Regular onset followed by prolonged break in monsoon conditions;
(iv) Erratic behaviour throughout the season.

Fortunately, it is possible to build a period-fixed character coupled with some resilience to seasonal conditions, through the intelligent use of genes for relative insensitivity for photoperiod and temperature and for early seedling vigour and speedy root development.

(e) Raising the ceiling to yield in pulses and oilseeds: Sinha and Swaminathan (1981) have discussed in detail the plant breeding approaches that may be of value in raising the ceiling to yield in energy-rich crops like grain legumes and oilseeds. In addition to total harvest index, studies on nitrogen harvest index are important (table 10). If a multi-pronged, interdisciplinary thrust is not launched, the outlook for these crops will not be bright, as the current situation indicates (table 11).

Table 10 *Species and cultivar difference in harvest index and nitrogen harvest index in Wheat* (Triticum aestivum) *and Chickpea* (Cicer arietinum)

	Harvest index	N_2 harvest index
**Wheat cultivars*		
Little joss	36	71
Holdfast	36	69
Hobbit	48	72
Benoist 10483	48	73
Chickpea cultivars		
JG-62	23	46
M-109	30	51
M-119	35	69

**Based on Austin et al. 1980*

Table 11 *Changes in crop output from 1949–50 to 1979–80*

Crop	(Million tonnes) Average annual production 1949 to 1952	Average annual production 1977–78 to 79–80	Percentage increase
Rice	23.26	49.54	112.98
Wheat	6.64	32.94	396.08
Total Cereals	47.68	110.55	131.86
Total Pulses	9.45	10.84	14.71
Total food grains	57.14	122.39	114.18
Oil Seeds	4.96	8.77	76.81
Sugarcane (Gur)	6.96	15.67	125.16
Cotton (lint)	3.02	7.63	152.65
Jute	3.92	5.97	52.30

(f) Location specific varieties: For a variety of reasons, regional imbalances in productivity improvement in major crops are continuing to grow (table 12). Although technology by itself cannot remedy the situation, plant breeders have a particular responsibility to step up their efforts in breeding location specific varieties which can perform better under a given socio-economic and agro-ecological milieu. Varieties will have to be developed for zero, low and high input conditions.

Emerging possibilities in techniques of genetic recombination

As stressed so far, agriculture in the 21st century should depend on new strains of plants capable of producing high yields of high quality foods with minimal amounts of inputs in terms of water, fertilizers and pesticides. Recent developments in our understanding of biology at molecular level seem to indicate distinct possibilities of production of such strains. The kind of effective and creative relationship between agriculture and plant molecular biology required for restructuring the crop-plant genomes has begun and new material and ideas are now emerging. This new type of genetic engineering involves the use of recombinant DNA technology to quantitatively isolate and study, mutate and or transfer fragments of DNA in plants.

Recombinant DNA: A means of generating new variability

It is now well recognized that the genetic variability arising in nature from fusion of disparate DNA molecules by illegitimate recombination has played a key role in the evolution of organisms. Because a variety of genetic barriers limit the occurrence of such recombination events, the plant breeding programmes based on sexually or asexually derived interspecific hybrids have generally proved of limited value in broadening the genetic pool of crop plants. However, the recombinant DNA technology now allows experimental approaches to recombine DNA molecules irrespective of their source, in the laboratory.

Progress in recombinant DNA technology

Origin of this development is due to successive advances in the studies of molecular-genetics and enzymology of DNA mechanics in bacteria over the last twenty

Table 12 *Highest and lowest average yield of crops (1975–80)*

Crop	Lowest Yield		Highest Yield		Ratio of
	State	kg/ha	State	kg/ha	(5) to (3)
(1)	(2)	(3)	(4)	(5)	
Rice	Orissa	896	Punjab	2887	3.2
Wheat	Karnataka	667	Punjab	2449	3.7
Cereals	Rajasthan	682	Punjab	2307	3.4
Pulses	A. Pradesh	274	Punjab	879	3.2
Food grains	Rajasthan	612	Punjab	2175	3.2
Oilseeds	Himachal Pradesh	318	Tamil Nadu	971	3.0
Sugarcane	Madhya Pradesh	30684	Tamil Nadu	96982	3.2
Cotton	Maharashtra	72	Punjab	351	4.9
Jute	Bihar	964	Orissa	1509	1.6

years. The material and techniques developed for manipulation of bacteria remain the essential material for research directed on plants. The efforts on plants are being complemented by parallel work in animal systems. Currently, the primary objective of research with recombinant DNA in plants is to develop material that will aid in the elucidation of the organization of nuclear, mitochondrial and chloroplast genomes and the mechanisms by which the various genes are regulated. This work is expected to lay the foundation for future applications. The current technology involves isolation of specific gene(s) as DNA clones, alteration of genes and their use in transformation of suitable recipients. Some important information about these steps is given below. (See also Abelson 1980, Bogorad 1979 and Brill 1981).

Gene cloning

Preparation of vector DNA is one of the first steps of the procedure that results in cloned DNA. The nature of cloning-vector decides the usefulness of the final cloned product. Adequate vectors are usually small amplifiable replicons that can propagate readily in either bacteria or yeast cells. In experiments where the cloned plant-DNA is to be used mainly such as a probe or source for recloning, it is quite advantageous to use the vectors as Lambda, MI_3 *mpl* and pBR_{322} which have been derived from phages and plasmids of *Escherichia coli*. However, if the cloning-vector is to cross the bacterium-plant barrier, it must be able to replicate both in plant and bacterial cells. Such vectors are being constructed by recombining the *ori*-DNA segments of vectors such as those mentioned above and the segments of DNA essential for replication of plant virus genomes (cauliflower mosaic virus) and in cytoplasmic DNAs of different plants [chloroplast **(ct)** DNA, mitochondrial **(mt)** DNA and mt-plasmid S-DNA]. Still another category of vehicles is required for carrying out stable insertions of foreign genes into plant nuclear DNA. Besides the double replication origin, such derivatives will be carrying blocks of genetic information required for integration of the cloned genes into recipient DNA. Some of these important properties are exhibited by the natural Ti plasmid **(pTi)**. The phytopathogenic *Agrobacterium tumefaciens* bacteria carrying pTi acquire oncogenic properties. Such bacteria transfer a small segment of pTi DNA to plant cells which as a result produce tumors. The pTi has been successfully employed as a vector for stable maintenance of a foreign gene in a plant. This vector system already holds great promise. However, considerable work is in progress to further tailor pTi and other available vectors and to search for still better natural vectors that can efficiently integrate a single copy of the cloned gene carried by them into host genome.

The source DNA is dissected in orderly fashion using DNA restriction endonucleases. The products are extremely complex mixtures from which individual restriction fragments to be cloned are purified. Alternatively, specific DNA fragments for cloning are obtained as reverse transcription products of purified mRNA species. Such blunt-ended DNA molecules are added to known complementary single stranded tails at the two ends, enzymatically. The vector DNA is similarly treated such that linear vector DNA molecules having single stranded tails complementary to those on the DNA to be cloned are generated. Usually T4 DNA ligase is employed to ligate the hydrogen-bonded vector-foreign DNA hybrid molecules. A variety of schemes based on the genetic properties of the vectors allow enrichment or selection and sometimes expression of cloned DNA in hosts such as the well-studied organism *E. coli*.

Diverse nuclear- and organelle-DNA fragments from Different plants have already been cloned. Complete libraries have been formed of ctDNA and mtDNA of the pea plant. Partial libraries of their nuclear DNA are also in existence. There are partial libraries of the three kinds of DNAs from a number of other plants. Some of the important nuclear genes that have been cloned are gene for phaseolin G1-globin of French bean plant, several leghemoglobin genes of soybean plant, and the gene for small subunit of ribulose biphosphate carboxylase (RUBP case) of the pea plant. These three genes do not seem to express in *E. coli*. Nucleotide sequence analyses of these gene-clones have revealed that, in conformity with a variety of animal genes studied earlier, they contain intervening sequences or introns which interrupt the continuity of the genetic information. Contrarywise, the cloned *ct* genes for large subunit of RUBP case, derived from maize and wheat, have been found to function in *E. coli*. These genes appear similar to prokaryotic genes since their nucleotide sequences in clones have proved to be colinear with amino acid sequences of their respective in vivo products. The work just described illustrates the advances being made in the cloning and study of plant genes.

Site-specific mutagenesis of cloned genes

This technology aims at mutation induction in clones of natural genes at specific sites. Mutagenic agents are short segments of chemically synthesized DNA. Each such segment has ends where action of a specific restriction enzyme will generate sticky ends. The internal sequences of these segments, incorporate deletions, insertions or point mutations at predetermined sites. The synthesized segments are inserted in place of corresponding normal segments by use of restriction enzymes and ligases. This technology has allowed detailed dissection of the roles of promoter and specific sequences in the *lac* operon of *E. coli* and based on the information so generated redesigning of the *lac* promoter. Following this model, a variant form of the naturally split human insulin gene has been synthesized and attached to promoter proximal segment of *E. coli lac operon;* the engineered operon functions efficiently in *E. coli*. This tool holds great benefit in plants. Using this technology it should be possible to make precise changes in the genes determining synthesis of storage proteins in grains and thereby improve the quality of foods. However, such applications await development of systems in which cloned genes can be transferred and studied for expression in a homologous milieu.

Transformation

Experiments with animal cells have resulted in the developmentof two general methods that can be used for reintroduction of cloned genes into original organism. The first is microinjection of DNA cloned on self-replicating viral vectors. Although use of viral DNA ensures synthesis of many copies of transferred DNA in recipient cells, the transformation is transient as the cell division products need necessarily not carry the transferred DNA. The second method involves transfection of specially derived cell lines deficient for functions controlled by the cloned genes. This approach yields both stable and unstable transformants. Transformation experiments with cloned DNA have not succeeded so far in plant systems. It is clear however that selective procedures will have to be developed for the isolation of transformants. Plant cells whose walls have been enzymatically stripped will be ideal to carry out transformation. Conditions created by treatment with polyethylene glycol or calcium ions at higher *p*H values might allow fusion of plasma membrane of protoplasts with those of bacteria carrying cloned genes and result in incorporation of foreign DNA into plant cells. It may also be possible to transfect cloned DNA into plant protoplasts by coating the foreign DNA with plant membrane proteins. Transformation of organelle genomes will involve greater skills. DNA may have to be first introduced into organelles and then organelles introduced into the protoplasts. Provision will also have to be made for stable inheritance of transformed organelles. Obviously great research effort will be required to develop transformation technology suitable for nuclear and organelle-genomes of plants.

Applications

It is generally recognized now that the most important applications of recombinant DNA technology will come in providing solutions to problems in food production and energy resources. New strains of plants will be developed to solve the problem of scarcity of inputs in agriculture. Photosynthesis will be most likely engineered to harvest fuel substances from sunlight. The approaches outlined below to achieve the above objectives may seem to be full of difficulties, but surely they will be solved slowly as the methodologies required for the tasks are already developing.

(1) *Conversion of cereals into nitrogen fixing plants*

(a) Certain bacteria synthesize an enzyme called nitrogenase which converts atmospheric nitrogen to ammonia. A group of such bacteria (Rhizobium sp.) are capable of inducing nodules on the roots of leguminous plants. The bacteroides in the nodules fix N_2 under protection from O_2 provided by leghemoglobin synthesized by the host plant. The specificity of susceptibility to Rhizobia in leguminous plants is due to their capability to produce lectin proteins that direct bacterial invasion of root tissues. If the leguminous lectin and leghemoglobin genes can be moved to the cereal plants, the host range of Rhizobia could be extended to these important food plants.

(b) A cluster of genes determine the synthesis of the enzyme nitrogenase in bacteria. The *ct* DNA in plants codes for conversion of ammonia to glutamine and also provides machinery for expression of prokaryotic genes. If the *nif*-genes can be transferred to chloroplasts nitrogen fixation will occur in them, provided chloroplasts are mutated such that O_2 evolution is eliminated. If the *nif*-engineered and normal chloroplasts are made complementary for their maintenance, plants could be produced which will have chloroplasts as well as nitroplasts.

(2) *Resistance to viruses and other pathogens*

(a) Phenomenon of negative complementation can be employed to control a variety of pathogens (viruses).

(b) A number of weed plants synthesize chemicals that render them resistant to various kinds of pests. If the concerned genes can be transferred to crop plants, the latter can be made inherently pest resistant.

(3) *Improvement of nutritional quality of pulse and cereal grains*

(a) It may be possible to engineer seeds that overproduce storage proteins. This kind of technology has been perfected in bacteria.

(b) The quality of storage proteins produced in grains can be changed by the site-directed mutagenesis technology such that all the essential nutritional requirements of humans can be met by the grain proteins only.

(c) It should also be possible to integrate genes of specific animal proteins in place of the storage protein genes.

(4) *Construction of male sterile lines for hybrid seed production*

Certain plasmid molecules in mitochondria determine cytoplasmic male sterility (cms) and susceptibility to diseases (Texas maize). Recombinant DNA technology is the only means to eliminate unwanted genes from such mitochondria. This technology could also be used to transfer reengineered *mt-cms* genes across the species barriers.

Photosynthesis

(a) The efficiency of photosynthesis itself might be improved if the nuclear and or *ct* genes determining efficiency of light absorption, electron transport, protein pumping and high energy phosphate bond synthesis in the chloroplasts are re-assembled from the best sources.

(b) Reengineering of C_3 plants to carry out C_4 metabolism will be highly useful. It may be achieved simply by having both kinds of chloroplasts in the same cell, after making the two kinds of *ct* DNAs complementary.

(c) Restructured plastids might be produced to synthesize carotenoids, isoprenoids or other carbon skeletons. The plant cells will contain both normal and engineered chloroplasts so that photosynthesis can derive the other chemical conversions by sustaining plant growth.

(d) There is also the possibility of developing cell lines that will produce food or fuel in bio-reactors.

Basic research in molecular-genetics will lead to a practical outcome perhaps before the end of this century. We should not lag behind in this field of research, if we are not to lose our position of leadership in the field of plant breeding.

Conclusions

It takes several years to restructure the plant breeder's assembly line to meet new selection criteria. As we approach the 21st century, the negative impact of acute demographic pressures on land and water will grow. Farms will get smaller and farm land will be needed for several other purposes. The ecological infrastructure essential for sustained agricultural advance will continue to suffer damage. Famines of work will assume even greater importance than famines of food, since apart from absolute number, the age structure of the population will change leading to a fall in dependency ratio. Energy will become a critical limiting factor. Because of the high risks involved in farming, there will be shyness in reinvestment of profits in expanding the productive base of agriculture. The cost, return and risk structure of farming systems will influence the decisions of farmers on the choice of crops and input levels.

Obviously, plant breeders cannot find solutions to problems arising from socio-economic and socio-political factors. Nor can they find solutions to all the handicaps arising from man induced destruction of the environment, although they can breed varieties which can survive and give some yield under hostile soil environments and growing conditions. It is however within their capability to find methods by which productivity and stability of yield of crops can be enhanced. It is also possible to develop through plant breeding approaches diversified opportunities for gainful employment in rural areas. The need for non-renewable forms of energy can be greatly minimised. Our large irrigated area, abundant sunlight and rich human resource can be brought into productive and purposeful interaction through the evolution of new genotypes.

While the problems to be solved are difficult and challenging, fortunately powerful scientific tools are also becoming available. The late Dr T S Venkataraman, who helped to change the sugarcane scene in our country, said when chemical tools for inducing mutations became available, "Man has become Brahma (Lord of Creation)". Since then biochemistry and molecular biology have taken further rapid strides.

Gene implantations and recombinations can help to find solutions to some of the problems I have dealt with in this lecture. Globally, progress is in sight in the development of vaccines for foot and mouth disease in cattle, breeding of new varieties of non-legume crops that would fix nitrogen, and development of crops that can manufacture their own biodegradable pesticides or synthesize enzymes to break down fungal toxins. Techniques of protoplast fusion and organelle transfer, DNA and phage induced transformation and recombinant DNA cloning are all opening up new opportunities. The recommendation of the Science Advisory Committee to Cabinet for the immediate strengthening of biotechnology and genetic engineering research in the country hence needs to be implemented with speed and dedication. This will be the best tribute we can pay to Meghnad Saha, whose vision of an India made great and happy through the application of science to human welfare and happiness illumines the path we should follow.

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