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Chemistry and World Food Supplies

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The world is neither in danger of running out of food, as some assert, nor on the verge of eliminating hunger, as others contend. Thanks to improved agricultural technologies, practices, and policies, the world's farmers produced twice as much food in 1980 as they did in 1950 (*1*). Moreover, the world is still capable of meeting substantial increases in global demand for food. Even with this evidence of success, however, per capita food production in the developing countries increased little in the past decade, and actually declined in some of the poorest countries (*1*). Disparities in population and income growth severely skew the distribution of available food supplies, even at record production levels. These combined forces of population growth and rising incomes are limiting the availability of food for the poorest nations and poor people within all nations. For the remainder of this century and beyond, agriculture will confront a dual challenge: to make a minimally adequate diet available for all, while simultaneously satisfying the market demand of growing numbers who can afford better quality food.

This challenge must be met primarily in the developing nations, where three-quarters of the world's population will live by 1990, and where the demand for food is rising fastest. In Asia, where more people will live by the year 2000 than in all other developing regions combined, the only realistic means of accelerating food production is to increase yields and intensity of cropping on land that is already under cultivation. In Africa, with declining per capita food production and an already serious food deficit that is projected to increase sevenfold by the year 2000, new land can still be developed for agriculture—but only with new technology, substantial economic resources, and many more trained people. Newly developed lands will also probably provide for much of the increased food needs of Latin America.

Food production is constrained by a myriad of factors, some social and economic, others physical and biological. In this article I focus on a few of the physical and biological factors that affect crop production. Whatever the approach or combination of approaches within a given region, chemistry will have a strong hand in determining the amount of food available for human consumption in the coming decades. An optimistic outlook is justified by a brief review of the contribution that chemistry has already made to food production, particularly in the developing countries, since the advent of the Green Revolution.

Summary. Much of the unprecedented increase in developing countries' food production in the past two decades is due to chemical-based technologies and to the use of agricultural chemicals. However, these successes were won under generally favorable conditions of soil, climate, and irrigation water availability. The challenge of the future is to broaden the base of increased food production to include areas less well endowed with natural and economic resources. Chemistry and chemicals must play vital roles in this venture. Innovative chemical and biochemical approaches must be called upon to produce crop varieties, animal strains, and associated technologies to overcome constraints such as insects and diseases, acid and alkaline soils, and drought conditions. Genetic engineering will probably be a primary mechanism to achieve this goal.

Role of Chemicals in the Green Revolution

The remarkable progress in food production in the developing countries over the past 20 years is due primarily to the development and adoption of fertilizer-responsive cereal varieties, especially of wheat and rice. Unlike the traditional varieties which they replaced, they are short-statured and upright-leaved. When fertilized, they resist lodging and convert a high proportion of their photosynthate to grain. Without fertilizer, even when irrigation water is available, their yields are only slightly above those of the traditional varieties. With both fertilizer and irrigation, however, field yields may be double or even triple those of the traditional varieties.

These modern varieties were quickly adopted by rich and poor farmers in areas where they were suitable (Table 1). The new wheats were largely responsible for India's increase in wheat production from 11.4 million metric tons in 1964 to 34.7 million metric tons in 1979 (*2*). Similarly, rice production in Indonesia rose from 12.2 million metric tons in 1970 to over 22 million metric tons in 1981 (*3*). The annual economic value of these production increases is in the $5 billion to $7 billion range for these two countries alone.

These yield increases were associated with comparable increases in fertilizer usage in the developing countries (*4, 5*). Since 1960, there has been an 18-fold increase in fertilizer use in India, with much of the increase being on cereal crops. In the developing countries as a whole, fertilizer use increased five times

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Table 1. Estimated area of high-yielding varieties of wheat and rice, and proportion of crop area planted to high-yielding varieties, in less developed nations (excluding communist nations, Taiwan, Israel, and South Africa), 1976 to 1977. [From Dalrymple (*64*)]

Region	Wheat	Rice	Total
Area of high-yielding varieties		*Hectares*	
Asia (South and East)	19,672,300	24,199,900	43,872,200
Near East (West Asia and North Africa)*	4,400,000	40,000	4,440,000
Africa (excluding North Africa)*	225,000	115,000	340,000
Latin America	5,100,000	920,000	6,020,000
Total	29,397,300	25,274,900	54,672,200
Ratio of area of high-yielding varieties to total area		*Percent*	
Asia	72.4	30.4	41.1
Near East	17.0	3.6	16.5
Africa	22.5	2.7	6.5
Latin America	41.0	13.0	30.8
Total	44.2	27.5	34.5

*Particularly rough estimate of area.

since the FAO base period, 1961 to 1965. The fertilizers were made available and farmers bought them with profits from the previous year's harvest (*6*).

In spite of the marked increase in the quantity of fertilizers used in the developing countries, the rate of application per hectare is still very low by the standards of developed countries. Most of the developing countries are still using less than 30 kilograms of nitrogen, phosphorus, and potassium per hectare of arable land (*7*). This compares with an average of about 100 kg/ha in the United States and more than 200 kg/ha in Japan and most of the populous countries of Europe (*7*).

Pesticides have also played a positive role in increased food production, although less so than fertilizers. Insect pests, diseases, weeds, and rodents are serious constraints to food production, especially in the humid tropics. Scientific efforts to remove these constraints have focused on the breeding of resistant varieties of crop plants, as well as on the development of new pesticides. The containment of rat infestations of rice paddies by the use of rodenticides is a good example of the importance of pesticides, as is the use of insecticides to control the Brown Planthopper, an enemy of the rice plant from the tropics to Japan.

The quantities of chemical pesticides applied in developing countries are minor compared to those used in the industrialized countries (*8*). Furthermore, most of the pesticides are applied to exported crops, such as cotton and bananas, rather than to locally consumed food crops. Herbicides for weed control are used in larger quantities than insecticides or fungicides.

Several factors have restrained the use of pesticides in developing countries. First, the high costs of developing, testing, and evaluating these chemicals have discouraged pesticide companies from focusing on specific problems in the less developed countries. Most of the chemicals used are those already found to be effective in the more developed countries. Second, low usage rates have prevented the economy of scale needed to provide the chemicals at prices which poor farmers can afford. Third, low-income farmers often do not have the technical skills nor even the simple hand equipment needed to effectively use the pesticides. Last, under the continuous cropping conditions in some parts of the tropics, insect pests and diseases quickly develop resistance to the pesticides, undercutting their effectiveness.

The yield increases associated with the Green Revolution cannot be attributed to the use of chemical products alone, of course. Crop yields are closely correlated with the area of cropland under irrigation. However, even when irrigation is available, full yield potential cannot be achieved without good soils, adequate plant nutrients, and reasonable control of plant pests. Although I will now focus on other factors, the concomitant importance of water supply cannot be overlooked.

Future Challenges for Chemistry in Food Production

The highest food production increases of the past two decades have been obtained in the most favorable environments—areas with good soils, controlled water supplies, the least risk from pest damage, and easy access to markets. While it is likely that much of the production increases of the next two decades will come from these same favored areas, an increasing proportion must come from regions less well endowed with favorable natural and biological environments. Chemistry will play a critical role in developing technologies to make these less well-favored areas more productive.

Although animals are important sources of food, particularly protein, for the developing countries, the production of animals is also dependent on the availability of plants. Thus plants will continue to be the primary source of increased food production, particularly in areas where the ratios of population to cultivable land are high. Increased production will come from both cropland expansion and increased yields per hectare in Africa and Latin America, but will be limited mostly to higher yields on currently cultivated lands in Asia.

Problem Soils

Among the most critical constraints on production in developing countries is that of problem soils. Nobel laureate Borlaug recently said that "Without doubt, the single most important factor limiting crop yield on a worldwide basis is soil infertility. Lack of one or more essential nutrients is usually the joint effect of weathering followed by leaching and erosion combined with extractive farming practices" (*9*). However, most of the high-yield seed varieties of wheat, corn, and rice developed by Borlaug and others are inapplicable for large areas of the developing world because of adverse soil conditions such as the build-up of salts, iron or aluminum excesses, or high acidity (*10*).

That chemistry may provide approaches to improving soil conditions is shown by the data of Cochrane and Sanchez (*11*) in Table 2. On the basis of a Fertility Capacity Classification System, these authors identified the major chemical and physical constraints for the Amazon Basin in South America. They demonstrated that 90 percent of the area is deficient in phosphorus and only about 16 percent has a high phosphorus fixing capacity. Aluminum toxicity and highly acid soils characterize nearly 75 percent of the area. About one-sixth of the area has low cation exchange capacities and would be expected to easily lose nutrient cations by leaching.

The fragile fertility status of some upland soils (Oxisols and Ultisols) of the tropics is illustrated by the rapid decline in food crop yields when the land is not fertilized. In one experiment in Peru performed by scientists from North Carolina State University (*12*), upland rice

Table 2. Summary of the main soil constraints in the Amazon Basin under native vegetation. [From Cochrane and Sanchez (11)]

Soil constraint	Millions of hectares	Percentage of Amazon Basin
Phosphorus deficiency	436	90
Aluminum toxicity	315	73
Low potassium reserves	242	56
Poor drainage and flooding hazard	116	24
High phosphorus fixation	77	16
Low cation exchange capacity	64	15
High erodibility	39	8
No major limitations	32	6
Steep slopes (>30 percent)	30	6
Laterite hazard if subsoil exposed	21	4

yields dropped from 2.9 tons per hectare for the first crop to 1.61 tons per hectare for the second crop and 0.6 tons per hectare for the fifth crop.

This rapid decline is most serious where "slash and burn" or shifting cultivation is followed. More than 240 million people in Africa, Asia, and Latin America eke out their subsistence using this system of cultivation (13). They clear the land and burn the vegetation from small plots, which are commonly located on steep slopes with infertile soils that are not highly prized for export crop production. The land is then cropped, usually with mixed plantings, for 1 to 3 years and abandoned (left fallow) in favor of another small site nearby. The fallowed land grows up in bush, savannah, or trees to permit the "regeneration" of the topsoil by bringing to the surface mineral elements from deeper soil horizons.

In the past, after 1 to 3 years of cultivation, the land was fallowed for 10 to 30 years or even longer, depending on the level of soil fertility. Such a system provided reasonable stability where population densities were no more than 20 per square mile (14). But today in some areas, population pressures have forced a shortening of the fallow period to 3 to 5 years, with a resultant fall in soil productivity and markedly increased soil erosion. This is undoubtedly a factor in the decline in per capita production in Sub-Saharan Africa during the past decade.

One of the most serious scientific challenges of the next two decades is to develop farming systems to replace or improve native shifting cultivation systems. While the help of all scientific disciplines will be needed, chemists with knowledge about soils and plants will play a major role in meeting this need.

Some progress has been made in ascertaining the potential of fertilizers and lime to economically increase food production in areas where shifting cultivation is practiced. For example, experiments in Brazil and Peru reported by Sanchez (12) suggest that modest fertilizer and lime additives can produce economical increases in crop yields, reduce aluminum toxicities in the soils, and provide a relatively stable cropping system. Much more research is needed to determine the extent to which these results are applicable.

Nutrient Supply and Utilization

Inefficient crop use of applied and soil-bound nutrients is a serious constraint on production in developing countries. Fixation of applied phosphates by oxides of iron, aluminum, and manganese and by certain silicate clays greatly reduces the effectiveness of phosphate fertilizers, especially in highly weathered acid soils. But the enormous losses of applied nitrogen provide perhaps the most significant challenge to chemists and biologists alike.

The current and future role of nitrogen in crop production in less developed countries is critical. The availability of this element is clouded by fluctuating energy costs. The production of 1 ton of nitrogen requires the energy equivalent of seven barrels of oil (15). Future food production will depend on the extent to which biological fixation of nitrogen can be more fully utilized, and on methods of increasing the efficiency with which crops use soil and fertilizer nitrogen.

Nitrogen losses. Rising energy costs have led to a research focus on the notoriously low efficiency with which plants utilize inorganic nitrogen, especially that added in fertilizers. Much of the nitrogen mineralized by soil microorganisms or added in fertilizers is lost either by leaching or volatilization (16, 17) (Fig. 1). Upland crops commonly recover only about 50 to 60 percent of nitrogen added in commercial fertilizers. For wetland rice, a figure of 25 to 35 percent is more common (18). Two-thirds or more of the applied nitrogen is volatilized as ammonia gas (19) or through denitrification as N_2O or N_2, or it is fixed by soil clays or immobilized in the soil organic matter (20). Figure 2 shows the types of nitrogen reactions occurring under wetland conditions (21).

Attempts have been made to control nitrogen loss by (i) developing slowly available nitrogen compounds, (ii) encapsulating or coating conventional fertilizers with a chemical that reduces the rate of nitrogen availability, and (iii) nitrification inhibitors that keep the nitrogen in the ammonium form, thereby reducing the risk of its being lost by leaching or volatilization.

Oxamide, modified urea formaldehydes, and isobutylene diurea are examples of compounds that slowly release their nitrogen in soils (22). Because of their high cost, their use is usually limited to high-value crops. Compounds potentially useful as nitrogen fertilizers have been reviewed by Murray and Horn (23).

Sulfur-coated urea is the most widely tested of the coated nitrogen fertilizers. Yields have been increased over those obtained with noncoated urea, especially with rice (22, 24). But the higher cost of the sulfur-coated urea has negated much of its yield advantage and has impeded the widespread use of these coated materials.

Nitrification inhibitors have also been widely tested as means of reducing nitrogen losses. Thiourea, dicyanodiamide, nitrapyrin, and several triazines have been patented as nitrification inhibitors (25) and have been widely tested in the United States. Their use appears to be economic under high rainfall and other conditions where high leaching losses would be expected (25). But the inconsistency of results obtained will probably limit the usefulness in the developing countries of currently available nitrification inhibitors. Low-income farmers cannot afford the risks of using these compounds.

Continued efforts must be made to reduce the losses of applied fertilizer nitrogen. Root zone placement of the fertilizer reduces these losses (26) although there is still no available simple, practical machinery which can properly place the fertilizer and which small farmers can afford. The search for means of reducing fertilizer nitrogen loss is one of the most significant challenges facing chemists and biological scientists.

Fixation of nitrogen. Increased fertilizer costs have focused attention on bio-

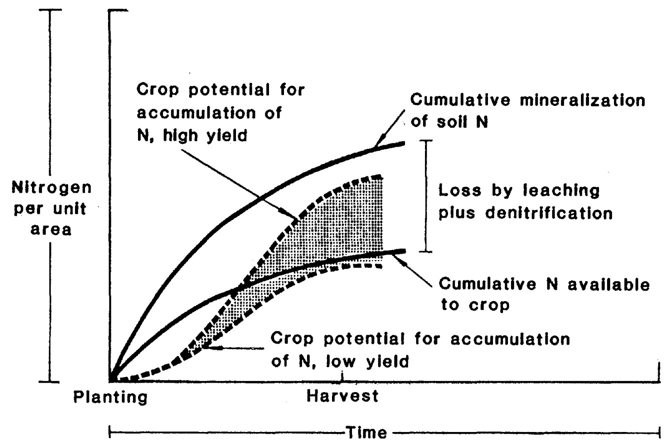

Fig. 1. Nitrogen as a constraint in the production of nonlegume crops. The data show the conceptual relationships among various nitrogen components in the crop-soil system during the cropping season. The solid lines represent the supply functions and the broken lines represent the potential of the crop to accumulate nitrogen under conditions of adequate supply. [From Bouldin *et al.* (*16*)]

logical means of providing the nitrogen needed for increased crop production in the developing countries. In the past decade scientists in both developed and developing countries have redoubled their efforts to learn more about the biological nitrogen-fixation process, and considerable knowledge has been gained (*27–30*).

One major benefit of this research has been the discovery that several other organisms, in addition to the rhizobia associated with legume crops, are capable of nitrogen fixation. A number of bacteria that are either free-living or occur in the rhizosphere of grasses (*29*), certain blue green algae, especially associated with the water fern *Azolla* that grows in wetland soils (*31*), and various actinomycetes associated with *Alnus* and other trees or shrubs (*32*) can fix nitrogen. An *Azolla-Anabaena* complex can fix 300 to 450 kg of nitrogen annually under wetland tropical conditions (*33*). The Chinese have long used *Azolla* as a source of nitrogen on some 1.3 million hectares (*34*). Although knowledge of the fixation processes used by all of these organisms is sketchy, and no practical methods of increasing the quantities of nitrogen fixed have been discovered, some information about the chemistry and genetics of biological nitrogen fixation has emerged from recent research (*35*). Nitrogen fixation by pure cultures of *Rhizobium* is now possible, making it easier to evaluate factors affecting the process. Mutants of rhizobia have been isolated and linkage maps have been constructed for some of these organisms (*36*). Recently, a fast-growing *Rhizobium* species was isolated from soybean nodules collected in China (*37*). Much more research is needed on the identification and application of strains of bacteria with high nitrogen-fixing abilities.

Studies have shown that high rates of biological nitrogen fixation are associated with substantial energy requirements. Rates of photosynthesis appear to limit nitrogen fixation in some plants (*38*), reaffirming the truism that "there is no free lunch." Recent evidence suggests, however, that the photosynthetic rates may be higher in nodulated than in unnodulated legumes, indicating that the legumes may in part adjust for the increased energy demand brought on by nodule formation and nitrogen fixation (*39*). Marked differences in the efficiency of nitrogen fixation (*40*) have been found to be due to the loss of H_2, which, in efficient strains of organisms, is recycled by a hydrogenase (*35*).

Progress has been made in developing analytical techniques to quantify nitrogen fixation and assimilation. Achievements include determination of the activity of the nitrogenese enzyme by the reduction of acetylene to ethylene, ascertaining the source and path of nitrogen assimilation by means of nitrogen-15, and the detection and translocation of nitrogen compounds known to have been produced in the fixation process. Allantoin and allantoic acid, two ureides derived primarily from nitrogen fixation in root nodules (*41*), are being used to detect soybean lines with superior nitrogen-fixation potential.

Efficiencies in chemical fixation of fertilizer nitrogen also offer significant potential for reducing energy requirements for agriculture. An analysis by Mudahar and Hignett (*42*) of the energy requirements in present fertilizer factories shows that the potential energy saving in producing 1 ton of urea is 25.5 gigajoules, or one-third of present use. This is equivalent to saving more than 0.5 ton of naptha or gas per ton of fixed nitrogen.

Pest Management

Although the management of insect pests, plant and animal diseases, weeds, and rodents will probably continue to depend principally on nonchemical methods of control, chemicals will remain an important component of integrated pest management systems. For example, synthetic organic pesticides (*43*), will probably continue to be of value in these systems in spite of their

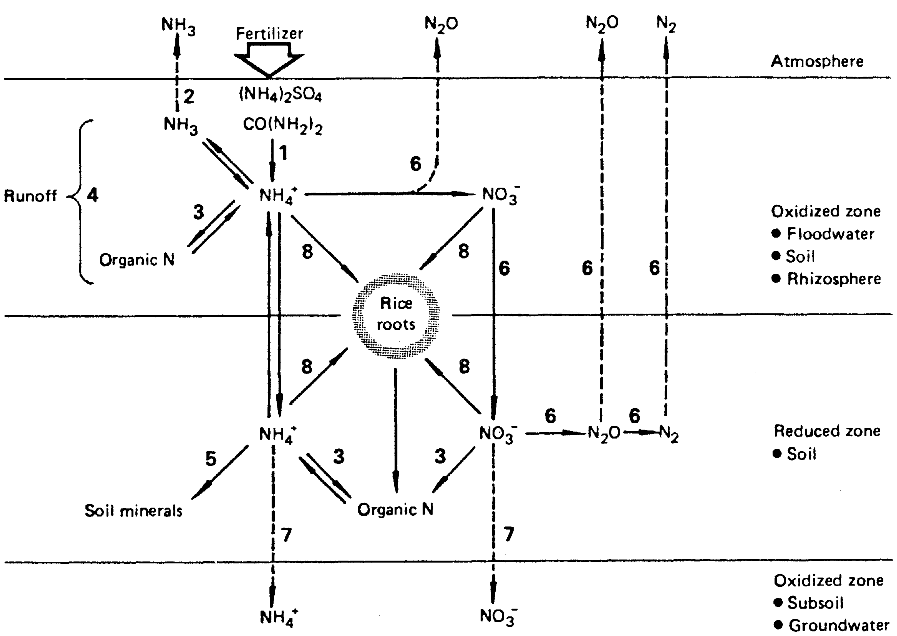

Fig. 2. Fate of fertilizer nitrogen applied to wetland rice. Numbers relate to the following processes: 1, urea hydrolysis; 2, ammonia volatilization; 3, nitrogen immobilization; 4, runoff; 5, ammonium fixation; 6, denitrification; 7, leaching; 8, plant uptake. [From Craswell and Vlek (*21*)]

potential hazards to humans and animals.

The shift from organochlorine to organophosphate pesticides has increased the problem of human pesticide poisonings worldwide, and the magnitude of this problem is still not known (*44*).

People in the developing countries are becoming more aware of the long-term problems posed by the use of chlorinated hydrocarbons and highly toxic organophosphates. In many countries, however, these pesticides are still sold and used indiscriminately. High rates of use have generated widespread insect resistance (*45*), which in turn has required increases in the frequency and number of pesticide applications to achieve the same degree of control. A related problem, which has already appeared in parts of the U.S. Corn Belt and may be anticipated in the developing world, is the occurrence of chemically induced changes in the microbial populations of soils with a history of heavy pesticide application (*46*).

This state of affairs is not inevitable. The U.S. Agency for International Development (AID) has found that small farmers in developing nations are quite capable of using carefully selected pesticides that have acceptable toxicological profiles. To further this end, AID regulations now require all pesticides recommended for the projects it supports to be reviewed for their potential effects on humans and the environment (*47*).

With the expectation that Third World agriculture may make increasing use of chemical products, information on costs versus benefits must be obtained. For example, the use of herbicides for "no-till" agriculture may at first glance appear to be inadvisable in developing countries, given the surplus labor available for hand-weeding, and the need to minimize the use of petroleum-based inputs. However, the increased dividends gained from decreased soil erosion, optimization of planting dates, and maximum utilization of soil moisture frequently combine to tip the balance in favor of herbicide use. Minimum till or no-till methods are particularly advantageous for upland cropping on steep slopes where the erosion of tilled soil is a serious problem. Little or no field preparation is required immediately before planting, loss of existing soil moisture is minimized, and the remaining crop and weed residues protect the soil from erosion. In warm climates, planting can be done earlier than usual, thereby increasing the probability of cropping with the same rainfall. In addition, since the peak farm labor load frequently coincides with the period of maximum weed growth, manpower usage can be more effectively regulated. Research on conservation tillage agriculture in developing countries is now under way at the International Institute of Tropical Agriculture and at the International Rice Research Institute.

Another approach to weed control with chemicals is the use of growth regulators to stimulate the germination of weed seeds. For example, maize, a major host plant of the parasitic weed *Striga*, contains a chemical substance (strigol) that can selectively initiate germination of witchweed seeds. If the chemical is applied at the correct time, the witchweed seed can be made to germinate in the absence of the host corn plant, and the weed seedling dies before it can become attached to the corn plant. A similar approach to important Third World weeds (for example, *Striga* species and *Orobanche* species) is now being investigated by the Department of Agriculture: gaseous ethylene is injected under the soil surface to cause premature germination of the weed seed (*48*).

In addition to continued research on new synthetic chemical pesticides, much effort in the last decade has been expended on chemicals that mimic the actions of naturally occurring products. For example, the synthetic pyrethroids have been promoted recently within the developing countries, sometimes even before they were fully accepted by the developed nations. Also, chemicals that inhibit specific enzymatic processes, such as chitin synthesis, have been found to be of use. One of these, diflubenzuron, is playing a key role in the management of cotton pests within the context of an integrated pest management program (*49*).

Naturally occurring pesticides appear to be ubiquitous (*50*). In addition to those whose modes of action involve acute toxic effects, the insect hormones represent an important group. Of these, the juvenile hormones have received the most attention (*51*). Because of their relatively short persistence and the short developmental period during which they are active, these natural products have not been extensively commercialized. An exception is methoprene, a somewhat more stable commercially produced synthetic analog which has been successfully introduced for certain specialty uses. Antijuvenile hormone activity was discovered in plants by Bowers *et al.* (*52*) and the synthesis of analogs of such structures may well lead to new breakthroughs in insect control.

One interesting plant, the Neem tree (*Azadirachta indica*), has been the subject of insecticide research. Extracts and powdered seeds from this plant show promise in the management of several insect pests causing problems in developing countries. The seeds and leaves yield azadirachtin, a compound that appears to be a promising new insect repellent. It is a systemic pesticide that is absorbed into a plant and works from within. Many insects will starve before they will eat plants treated with azadirachtin (*53*). In addition to containing highly potent antifeeding agents, extracts exhibit growth regulation effects on certain species of insects.

Control of insect pests by chemosterilants, while theoretically feasible, has not been extensively adopted even in the developed world. This is because alternative methods of sterilization involving ionizing radiation are adequate (*54*).

Another area offering great potential is that involving sex pheromones. Several of these chemicals have been identified and synthesized in the laboratory. By means of techniques similar to those developed in China by Chiang, in which black light traps are used together with pheromones, these attractants should be useful in the detection of new infestations and for surveys of pest densities (*55*). Rose and Odiyo (*56*), using a combination of light traps and pheromone-baited traps, have developed an early warning system for the African army worm (*Spadoptera exempta*) based on differential trapping catches. The use of mass trapping techniques for insect population control is under study but no fully satisfactory methods have yet been developed (*57*).

The use of pheromones for mating disruption, while not expected to be of immediate utility in most developing countries, has long-term prospects—especially when the pheromones are microencapsulated in slow-release formulations (*58*). Other innovative means of using pheromones in integrated pest management have been reviewed recently by Silverstein (*59*). During the next decade these chemicals will probably be included in integrated pest management schemes in the tropics.

The role of chemical factors in insect-plant and pathogen-plant relationships will undoubtedly receive increased emphasis in the next decade as plant breeding programs yield new varieties of resistant crops. In addition to classical bioassay methods, rapid instrumental analytical procedures will be developed for screening for plant resistance once the active ingredients have been identified.

Innovative Means of Crop Improvement

Genetic modification and improvement of crop cultivars probably offer small-scale farmers of developing countries their greatest hope for the future. The seeds of new and improved cultivars offer the farmer an inexpensive and dependable means of development. New crop varieties are simple innovations that the farmer understands and that can be used as the nucleus of technological packages that the farmer will accept. The ready acceptance in the 1960's of new high-yielding wheat and rice varieties, along with the chemical packages that made them productive, illustrates this point. Small-scale, low-income farmers accepted the new technology almost as rapidly as did their higher-income counterparts. New seeds are perhaps the least costly means of providing new technology. It is much less expensive to produce varieties adapted to existing natural environments than to try to change those environments.

New and improved cultivars also offer practical means of overcoming production constraints. Genetic improvement has great potential for overcoming many limitations facing low-income farmers. In germ plasm collections around the world, the tens of thousands of crop cultivars offer remarkable variability regarding tolerance of adverse water and soil conditions; resistance to or tolerance of major insect pests and diseases; nutritional quality; and agronomic characteristics such as height, stem strength, and growth duration. Mutations stimulated by radiation or chemical mutagens can offer even greater variability. While great progress has been made in the past through traditional plant breeding methods, biochemical genetics and innovative biotechnology techniques offer even greater potential for the future.

By using the genetic diversity in the more than 60,000 accessions in the International Rice Research Institute germ plasm bank, scientists at that institution have incorporated resistance to six major rice insect pests and diseases, have shortened the 150- to 160-day growth duration to 90 to 110 days, and have discovered accessions with some tolerance to adverse soil and climatic conditions (*60*). Nearly 5000 crosses are made each year to achieve these results. Similarly outstanding results have been achieved at other national and international research centers.

Many of the constraints on production cannot be removed by traditional plant breeding techniques. Genetic materials with tolerance to some of the most serious crop pests and diseases and other production constraints have not been discovered. For example, tolerance of excess salts is not sufficiently high in some crops to permit them to grow in the tens of millions of hectares of otherwise suitable soils. Likewise, tolerance of very acid subsoil conditions in large areas in the tropics has not yet been identified for most food crops. Tolerance of drought and of high and low temperatures, while present to a degree in some genetic materials, is still not sufficiently high to provide disadvantaged, resource-poor farmers with seeds that are appropriate for their lands.

The hope of the future is that modern biotechnology will help provide the cultivars needed to overcome some of these production constraints. In the long run, techniques such as recombinant DNA technology, protoplast fusion, and the use of wide crosses, the development of truly pest-resistant plants, drought- and salt-tolerant varieties, and energy-efficient nitrogen-fixing bacteria may be achieved. While they will be of revolutionary value to U.S. farmers, these achievements will be even more helpful to the resource-poor farmers of the developing countries.

Cell and Tissue Cultures

Although some technical advances must await basic research findings, techniques for using cell and tissue cultures to help plant breeders are already at hand. These techniques are being used for the rapid propagation of some desirable plant lines and show promise as means for producing mutants, thereby increasing the diversity of the genetic pool. Cell and tissue cultures can also be used for the transport of sterile genetic materials from one country to another without the risk of spreading viruses, fungi, or other pathogens.

Cell and tissue cultures, known as "the gateway through which all forms of plant genetic engineering must pass," require close collaboration among chemists, plant pathologists, plant physiologists, and plant breeders. At a recent conference entitled Genetic Engineering for Crop Improvement (*61*), participants repeatedly stressed the need for greater teamwork and more trained personnel, including scientists from the developing countries. One high priority research task identified at this meeting as having a near-term impact was the development of appropriate biochemical methods for identifying useful genes—in conjunction with efforts to better understand the genetic control of agronomically important traits (*61*).

In a conference entitled Genetic Engineering: Applications to Agriculture, a number of promising developments were reported (*62*). A culture of wheat, for example, has produced plants with such properties as dwarfism. Tissue culture techniques have also resulted in the production of new rice lines with higher lysine and protein content. These developments are still in the greenhouse stage and have yet to be field-tested. One Beltsville scientist reported on the use of genetic techniques to develop a quick assay for potato lines that carry viroids but show no symptoms of infection.

The potential of tissue culture and other related biotechnology techniques is yet to be realized, but plant scientists are optimistic that dramatic results will probably be obtained and that significant benefits will accrue in the next 15 to 20

Table 3. Results obtained from a survey of scientists (*63*). Participants gave the date of the first significant contribution from each biotechnology to maize yield and expected contribution in the year 2000. [Courtesy of the American Institute of Biological Sciences]

Biotechnology	Date of first significant contribution	Expected contribution to yield in 2000 (kg/ha)	Number questionnaires mailed	Number questionnaires received
Photosynthetic enhancement	1995	497	22	18
Cell or tissue culture	1990	195	37	31
Plant growth regulators	1994	988	22	19
Genetic engineering	*	*	32	27
Biological nitrogen fixation	1996	142†	20	15

*This information was not specifically requested in the questionnaire for genetic engineering because the technology is in an early state of development in relation to corn production. †Nitrogen from biological nitrogen fixation was converted to maize yield equivalents as follow: 35.5 kg/ha × 44/11 = 142 kg of maize where nitrogen and maize prices are $0.44 and $0.11 per kilogram, respectively.

years. Menz and Neumeyer (*63*) recently reported the results of a survey in which scientists were asked questions relating to the potential of five emerging biotechnologies for increasing maize production. Table 3 indicates that there are great expectations for these modern techniques.

Conclusions

At no time in history has there been greater need for inputs by chemists to help the people of the world to feed themselves. Developments of the past 25 years have demonstrated clearly the role of chemists and other scientists in providing low-income farm families with the technologies that they need to increase food production. Great as these achievements have been, they are insignificant compared to the challenges of the future. Not only must an ever-increasing number of people be fed, but the extra food must be produced under inferior soil, climatic, and biological conditions. Between now and the time that the population stabilizes in the developing world (that is, within 30 or 40 years), every effort must be made by scientists in both developing and developed countries to provide new crop varieties, improved fertilizer technologies, and integrated pest management techniques that will permit sustained high yields of food crops.

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