PN-AAP-042

ISN 32999

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10th Anniversary Monograph Series
Asian Vegetable Research and Development Center

Correct Citation

Wittwer, Sylvan H. 1983. Frontiers for Science and Technology In Vegetable Production. Asian Vegetable Research and Development Center, 10th Anniversary Monograph Series. Shanhua, Taiwan, Republic of China.

AVRDC Publication 83-190

Frontiers for Science and Technology In Vegetable Production

Sylvan H. Wittwer[1]

There are hundreds of thousands of plant species, but less than 300 have been commercially cultivated worldwide as food crops. Of these, about half are classified as vegetables. Approximately 100 vegetables are listed as commercially grown in the United States and China, and 50 to 60 are commercially significant. In the state of Michigan, USA, 36 different vegetables are produced commercially.

Vegetables are grown primarily on land, but some are produced aquatically. They may be consumed as seeds, fruits, flowers, buds, leaves, stems, roots, and tubers (underground stems). In some cases, such as the winged bean, the entire plant may be used for food, and free-standing upright types are envisioned (39). About two-thirds of all known vegetables may be classified as cool season crops and one-third as warm season. Yet the majority of vegetables can be grown in most areas of the world by selecting for site and season (16). Vegetables generally have a short growing period but some are perennials. Many are consumed either fresh or in processed form. Technological changes, including mechanization, have progressed further with crops grown for processing than with those aimed at the fresh market. This is particularly true for vegetables that provide a good profit or are grown in large quantities. These include, for the USA, potatoes, tomatoes, peppers, onions, English peas, southern peas, sweet corn, carrots, snap beans, cucumbers, lettuce, broccoli, muskmelons, and sweet potatoes (35). Globally, some vegetables are considered major food crops (potatoes, sweet potatoes, soybeans, field beans, peanuts) and provide significant amounts of energy and protein. Most are valued as excellent sources of vitamins, minerals, and dietary fiber (1). The increased consumption of vegetables in many nations is a mark of the rising affluence of the people.

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Vegetables, with one or two exceptions, are seldom included in the statistics of international trade. World vegetable trade, where it exists, is mostly limited to exchanges between adjoining countries or those in close geographic proximity (16). Many vegetables are produced in home gardens and consumed directly by the producer. Some estimates have been made of their total dietary contributions to the human race, and they are significant for some nutrients (1,16).

This paper will address new frontiers for the science and technology of vegetable production, with primary focus on crops of worldwide significance. Biological resources that enable vegetable crops to utilize present environmental and natural resources more effectively will be emphasized (Table 1). Technologies derived

Table 1. The next generation of research for vegetable crops.

1.	Genetic engineering - cellular and molecular biology - cell and tissue culture - genetic diversity.
2.	Greater resilience to environmental stresses - cold, drought, heat, problem soils, and air pollutants - to insure dependability of production.
3.	Greater resistance to biological stresses including integrated pest management and disease resistant varieties.
4.	Biological transformations - nitrogen fixation, mycorrhizal root interactions, nitrification, denitrification, "bacterization", protein synthesis.
5.	Hormonal mechanisms - control of plant growth, flowering, fruiting, seed production, tuberization.
6.	Enhancement of photosynthesis, total metabolism, and differentiation processes for improvement of yields and harvest index.
7.	Alternative integrated, resource (land, water, energy, capital) sparing production systems.

from research focused on one or all of the areas identified would be scale neutral and appropriate for vegetables grown on farms of all sizes (48,51). Developing nations should be able to share the same comparative benefits and advantages as the United States and other industrialized countries in such research efforts. These frontiers of discovery are open to all. They are part of what can be termed a "biological revolution." Advances made by one nation and shared by others can multiply many times the benefits of such research investments.

Genetic Improvement - Genetic Engineering

Historically, remarkable progress has been made in the genetic improvement of vegetable crops. Indeed, plant breeders have been involved in genetic engineering for nearly a century. This is depicted in Table 2 by the wide array of F_1 hybrids that now exist and the extended periods for which many of them have been cultivated. Hybrids, however, are not yet available for all vegetables (Table 3), and there are challenges ahead in creating them, especially for most of the legumes and for a number of the leafy crops. The economic viability of vegetable seed companies will depend on the production of F_1 hybrids and the maintenance

Table 2. Vegetable crops for which F_1 hybrids now exist and the approximate years since their introduction.[2]

Crop	Approximate years since hybrid introduced
Sweet corn	40-50
Onion	40-50
Tomato	40-50
Summer squash	40-50
Ordinary cabbage	35-45
Cucumber	30-40
Watermelon	30-35
Muskmelon	30-35
Asparagus	30-35
Pepper	25-30
Spinach	20-30
Broccoli	20-25
Chinese cabbage	20-25
Eggplant	15-20
Brussels sprout	15-20
Chinese radish	10-20
Carrots	10-20
Red beet	5-8
Celery	5-8

Table 3. Some common vegetable crops for which F_1 hybrids are not yet available.

Celeriac	Lettuce	Parsnip
Chickpea	Lima Bean	Pea (garden type)
Collard	Mungbean	Pigeon pea
Cowpea	Mustard	Snap bean
Kale	Parsley	Soybean
Leek		Yardlong bean

[2] The suggestions of S. Honma, Professor of Horticulture, Michigan State University, are gratefully acknowledged.

of inbred parental materials. F_1 hybrids may not always be superior to open-pollinated varieties, however. Higher yields, greater uniformity, and earliness often characterize such hybrids along with disease resistance where a single dominant gene for resistance occurs. Resultant uniformity and narrow crop requirements can, however, lead to disaster on small subsistence farms.

There are many lesser known vegetables of potential for the future that offer opportunities for genetic improvement (Table 4). Many of these are of Chinese origin (18), and there is an ever-increasing demand for them in many parts of the world. The current trend of interest in oriental vegetables will likely continue during the decades ahead.

Table 4. Some lesser known vegetables of potential for the future (18,37).

Chinese cabbage *Brassica pekinensis* *Brassica chinensis*	Chinese yam *Dioscorea batatas*
Sponge gourd *Luffa cylindrica*	Taro *Colocasia esculenta*
Bottle gourd *Lagenaria leucantha*	Mo-yu *Amorphophallus rivieri*
Edible amaranth *Amaranthus tricolor*	Head mustard *Brassica juncea*
Garland chrysanthemum *Chrysanthemum coronarium*	Swamp cabbage *Ipomoea aquatica*
Chinese wolfberry *Lycium chinense*	Curly mallow *Malva crispa*
Chinese kale *Brassica alboglabra*	Basella *Basella rubra*
	Ginger *Zingiber officinale*

In addition to those listed above are the winged bean, yard long bean, cowpea, chickpea, udo salad plant, water oat, broad bean, burdock, lotus root, lotus seed, water chestnut, watercress, water dropwort, arrow-head, the great cattail, stem lettuce, and sprouts of bamboo derived from several genera and species. There are also varieties of cucurbits, including the wax gourd and the winter melon, and many types of peas and beans with high protein content (41).

Substantial efforts have been directed toward identifying and assessing research priorities in the plant sciences for horticultural crops (8). Control of the basic biological processes that limit both

the magnitude and stability of crop production is a central goal. These priorities are detailed in Table 1 as the next generation of research for vegetable crops.

Genetic engineering and the companion sciences of cellular and molecular biology as one front, along with cell and tissue culture technologies as a second front, are emerging as important nonconventional approaches to plant improvement (11). No less than 350 firms worldwide, ranging from large multinational to small venture capital units, have entered the field of biological engineering in the past five years. Most major vegetable seed companies have been absorbed by, have become integrated with, or have merged with chemical, petroleum, or pharmaceutical companies. The consolidation of seed and chemical companies provides potential for the development of networks for in-place breeding, reproduction, crop production and protection, and distribution. Some of the first applications of genetic engineering in vegetable production may be in the production of new, highly potent insecticides (30) and products that will control plant diseases. The report that human interferon retards the multiplication of tobacco mosaic virus illustrates a remarkable development (6).

Immediate applications of genetic engineering will likely occur as a result of microbiological production and tissue culture of specific vegetable crops (33). Cell and tissue cultures provide a convenient, efficient, and rapid method of plant propagation and provide for the establishment of experimental crossing lines. They are the gateways through which the developments of genetic engineering must pass to reach final utility in the field (2,3). Immediate opportunities reside with asparagus. Rapidly multiplied, superior plants can serve either as parents in producing F_1 hybrids or as selected materials for clonal multiplication. With asparagus, vegetative meristems (buds) may be cultured. These, in turn, produce small plants that may then be subcultured to produce and multiply the potential clones (Figure 1). With asparagus, tissue culture provides rapid multiplication of superior seed stocks with improved productivity, earliness, and spear quality[3].

Opportunities also exist with other crops (25). Most crucifers (Brussels sprouts, cauliflower, broccoli, cabbage) have the potential for rapid clonal propagation (multiplication) of large numbers of genetically superior plants, both for plant breeding purposes and for seed production. With potatoes, the potential is for virus indexing and production of virus free stock (34). Members of the onion family can be tissue cultured easily with the possibility of large numbers of explants (26). This is also true for spinach, beets, yam, and taro (Table 5). Tissue culture of vegetable crops has advanced to a high degree of technology in

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[3] The suggestions of Dr. Kenneth Sink, Professor of Horticulture, Michigan State University, on the subject of asparagus tissue culture are gratefully acknowledged.

Japan, Taiwan, and mainland China. Economic feasibility will dictate the future of micropropagation. Meanwhile, tissue culture is an extremely important resource tool and will be the path through which all forms of genetic engineering for plants must go if transitions are to occur from the laboratory to the field (2,11,33).

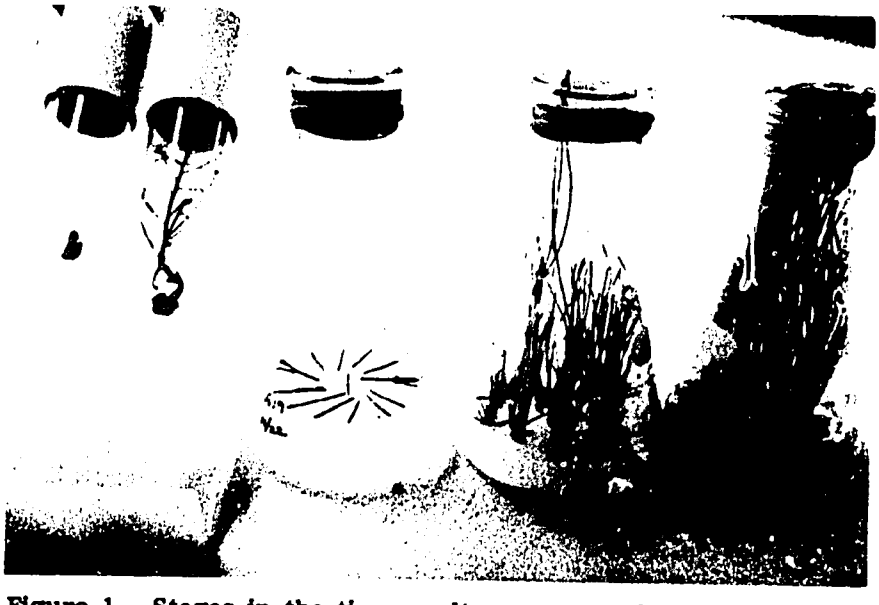

Figure 1. Stages in the tissue culture propagation of asparagus. Sequence begins (left) with a single bud or meristem. Stems are then progressively subdivided to form hundreds of clonal explants.

Table 5. Vegetable crops with promise for tissue culture propagation.

Asparagus	Cauliflower	Spinach
Beet	Eggplant	Taro
Broccoli	Garlic	Tomato
Brussels sprout	Onion	Welsh onion
Carrot	Potato	Yam

Greater Resilience to Environmental Stresses

Resilience to environmental stresses is considered the number one research priority for achieving high, stable production levels (8). The lack of dependability and the magnitude of annual variations in the production and availability of vegetable crops cause major year to year shortfalls, surpluses, and price disruptions.

Dependable crop production may be achieved through expanded irrigation of cultivated crops, both under dry and subhumid conditions. This is presently being achieved in mainland

China. Quantum increases in horticutural production may come, at least temporarily, from adding water to desert land. However, supplemental irrigation in semi-humid and humid regions combined with pesticides and the expanded use of naturally produced or synthetic fertilizer will insure dramatic and needed increases in the production, quality, and availability of most vegetables. In Taiwan, 65% of all cultivated land and most vegetables are irrigated. Irrigation with pest control can go a long way towards achieving production stability, but can not guarantee market stability.

Nevertheless, of all the resources involved in food production, weather and climate remain the most significant determinants for vegetable crop production and quality. More than any other factors, they account for the lack of year to year stability in production and quality. Improved resistance to environmental and climatic stresses - drought, heat, cold, problem soils, salinity (7), air pollutants (12) - through genetic improvement of crops and better management as designed and developed by researchers would stimulate the growth and dependability of production and crop quality. An example is phosphorus nutrition of onion plants, which has been implicated in the crop's ability to tolerate drought, the stress that farmers fear most. Mycorrhizal fungi improve phosphorus absorption during water stress and may be a major factor in improving drought tolerance (23). With input from several such lines of research, including the selection of genetic types that utilize low levels of nutrients, many sites now only marginally suited to vegetable production could become dependable producing areas.

There are many examples of the need for greater resilience of specific vegetable crops to environmental constraints. A bolting resistant heading Chinese cabbage is not yet available for production in the United States. Tomatoes face a problem, since both cold and heat inhibit fruit setting. Parthenocarpic fruit production is a possible solution and considerable progress is being made in this area.

Those engaged in vegetable variety improvement often test their new introductions under situations approaching the ideal rather than the marginal conditions encountered in "the real world." For the future we need to design varieties and cropping systems for the less than ideal conditions usually encountered at the grower level.

Seed and Seedling Viability and Survival

Improved seedling viability and survival is predicated upon greater protection against and resilience to environmental stresses. One approach is liquid and gel seeding for earlier establishment, better uniformity, and improved yields (5,13,31). This technology is now well advanced and is based on pregerminating the seed to produce enlarged radicals several millimeters long. The seed is then mixed in a gel solution in preparation for planting. The gel

suspends, cushions, and protects the seed as it is placed in the soil furrow. Options for gel seeding include sowing in continuous strips or in clumps. Pesticides can be incorporated into the gel to produce a disease- and weed-free micro-environment for growing seedlings. Nutrients and growth regulators may also be added.

Greater Resistance to Biological Stresses

Many pests afflict vegetable crops and large quantities of pesticides are used worldwide to control them. Ten to 30% of current production costs are incurred in the use of pesticides. With the exception of residues in the soil (40) and environmental pollution, the problems of pesticide resistance and the barriers to achieving effective control are usually greater in the tropics than in the temperate zones. One longstanding goal has been to decrease the quantities of chemical pesticides used in vegetable crop production, thereby reducing their unfavorable impact on the environment, lowering costs, and, at the same time, achieving an acceptable, economical level of pest control.

The management of pesticide resistance is emerging as a high research priority that will assume increasing importance in the future. There are now more than 300 insects, many afflicting vegetable crops, that are resistant to insecticides. The tiny diamondback moth in Taiwan is resistant to all 28 chemicals previously used for its control. It is the most serious pest of all cruciferous crops in the Far East and Southeast Asia (46).

The control of competing biological systems in vegetable production will not lie in the use of chemicals alone. An integrated approach resides in a combination of resistant varieties, cultural practices, biological controls, and chemical treatments. Frontiers for new science and technology in pest control will include studies on the nature of resistance to bacterial and virus diseases; computer programming of pesticide applications with pest control models built on "real-time" - on-line weather (climate) information, life cycles of pests, and predictable biological behavior of hosts; and, through genetic engineering, the identification of new, more powerful pesticides (30) and crop cultivars with built-in resistance.

There are other emerging technologies of importance in pest control for vegetables. None is more intriguing than the allelopathic properties of selected crops and their residues. It is well known that some plants retard the growth of others. This is an active biological process in desert environments. Many vegetable crops and their plant parts have been documented as having allelopathic properties. These include asparagus, Chinese cabbage, the mustards, cucumber, and potato. It seems likely that in the future appropriate plant residues can be utilized with new conservation tillage practices to reduce or even eliminate the now essential use of chemical herbicides on such crops as tomato,

asparagus, sweet corn, and beans[4].

Biological Transformations

The control of biological transformations, including nitrogen fixation, mycorrhizal interactions with roots, and reductions in loss of fertilizer nitrogen from nitrification and denitrification, will play an increasingly important role in vegetable production. A large number of legumes are identified as vegetable crops (Table 6). Specific selections of rhizobia infect the roots of these legumes. The potential for increased biological nitrogen fixation under field conditions has scarcely been tapped. Future efforts will relate to genetic improvements of the microorganism as well as the host plant.

Table 6. Some nitrogen-fixing *Rhizobium* species of significance in vegetable production.

Microorganism	Host	
R. japonicum	Soybean	
R. phaseoli	Common bean	
R. sp. (cowpea)	Cowpea	Pigeon pea
	Mungbean	Peanut
	Chick pea	Winged bean
R. leguminosarum	Broad bean	
	English pea	
	Lentil	

Basic research related to vegetable production from biologically fixed nitrogen is one of the most neglected of all the biological sciences. All vegetable legumes with associated rhizobia can fix atmospheric nitrogen (Table 6). Advances in this area will be prominent for increasing vegetable crop production in the future.

Nitrogen fertilizer is the single most important industrial input. Increasing amounts of nitrogen fertilizer, either from organic or inorganic sources, will be required for vegetable production. Additional renewable and non-renewable sources must be sought. Research on biological nitrogen fixation has been outstanding in producing sophisticated basic information, but little practical knowledge has been developed to increase vegetable crop production under field conditions.

Of equal importance are the mycorrhizae (soil-root-fungal) relationships. Mycorrhizae constitute a class of biological

[4] The suggestions of A. R. Putnam, Professor of Horticulture, Michigan State University, on allelopathy are gratefully acknowledged.

organisms of great importance for future vegetable crop production (4,23,32,38). These fungi colonize the roots of practically all vegetable crops. Some 80 species of fungi live in and around root surfaces (29). Root absorbing surfaces effective for water and nutrient uptake may be increased ten-fold by their presence. Phosphorus and many micronutrients are thus made more available to plants on otherwise phosphorus and nutrient poor soils. Nutrients are converted to more soluble forms and transported to the roots of plants. Mycorrhizae also favor nitrogen fixing bacteria. While mycorrhizae do not add nutrients or moisture to soils, they may influence the efficiency of crop removal of these essential growth factors. One of the most exciting scientific frontiers will be further studies of the physiology and biochemistry of rhizospheres.

Yet another area of interest is the efficiency and utilization of fertilizers applied to vegetable crops. In some cases, fertilizer losses range from 50-75%. Two microbiologically powered processes - nitrification and denitrification - are involved in losses of soil nitrogen. Nitrogen stabilizers or chemical nitrification or denitrification inhibitors may reduce losses. Chemical inhibitors for both nitrification and denitrification are now available (20). Losses from denitrification can also be reduced by good drainage and management.

Another approach to greater efficiency in utilization is the use of new fertilizer sources, such as sulfur-coated urea and super-granules of urea, and deep placement for certain vegetable crops. The increased cost and limited effectiveness of these materials and problems of handling and application have thus far detracted from their widespread use.

Another means of greatly increasing the efficiency of fertilizer usage is application through trickle irrigation systems (43). Here the value of the applied fertilizer, in some instances, may be doubled.

Still another approach toward increased efficiency in the use of chemical fertilizers for vegetable crop production may be through foliar applications. The history of leaf feeding is long and complex. Increased yields may be made possible by utilizing the absorptive capacities of the aerial as well as the subterranean parts of the plant, especially when applying nutrients at critical stages of development such as during the early stages of flowering and fruiting. Nutrients sprayed on aerial plant parts are absorbed but application technology is still lacking. Worldwide, and in many developing countries, there is extensive use of foliar feeding of vegetable crops. The rising cost of fertilizers and the fossil fuel resources needed in their application is providing a continuing stimulus for further investigations of the potential for foliar feeding. No comprehensive assessment of foliar fertilizer application has appeared since our report of 1969 (42). This is an instance where a technology has been adopted at the grower level and is being extensively applied in vegetable crop production, particularly for micronutrients, with little laboratory or field research to support the practice.

Hormonal Mechanisms

No area for future research and new technologies is more promising than that posed by the use of plant growth regulators. The effects are numerous (9,24,50). Responses range from increases in overall productivity and crop yields (Brussels sprouts, celery, globe artichoke) and improvements in quality (rhubarb, peppers, tomatoes) to prolonging the storage life of potatoes, onions, and root crops. Maturity may be hastened, fruit size increased, coloration improved, and uniformity of ripening induced. Almost all vegetable crops and their products can be favorably altered. Specific effects include improvement of fruit set and size, modification of flower sex expression, control of storage sprouting, flower formation, increased fruit and seed production, senescence inhibition, replacement of cold requirements for flowering and seed production, improved rooting of transplants, and concentration of fruit set for more effective harvesting. Growth regulators can serve as harvest aids for tomatoes and peppers. They can increase the uniformity and size of Brussels sprouts, and result in earlier production, higher yields, and prolonged harvest of globe artichoke and rhubarb. Tomatoes produced for processing in the United States are now ripened uniformly by preharvest chemical sprays of ethylene releasing chemicals. The productivity, uniformity, and color of major vegetable crops now grown for fresh market and processing are improved by growth regulator treatments. There is a potential for greater resistance to environmental stresses (heat, cold, drought, and air pollutants) following the use of growth regulators.

Photosynthetic Enhancement

No area is more important than greater photosynthetic efficiency and partitioning of photosynthates for the improvement of yields of vegetables and their harvest indexes. Yet most research with photosynthesis thus far has been directed toward further understanding the nature of the process rather than relating the results to improvements of crop productivity under field conditions. Some research initiatives related to enhancement of crop productivity through greater photosynthetic efficiency include fast initial growth for a high leaf area index, improved plant architecture with more erect leaves, delayed or slow senescence, the use of plant growth regulators, genetic selections for photosynthetically superior lines, reductions in photo- and maintenance respiration, and sustenance of a healthy root system. These are promising areas for future research on photosynthesis that could be translated into improved crop productivity (39).

Research with vegetable crops for the future should include maximum yield trials to explore the biological, technological, environmental, and resource limits of crop production. These limits have not been ascertained for any crop, although current world records for some provide an approach (47). Packages of

technology should be assembled for future research to further extend the limits of productivity and identify existing constraints.

Alternative Production Systems

Many new technologies are emerging for vegetable production. Some are listed in Table 7. One should be mindful of integrated vegetable producing systems that are being cited as alternatives to those which are now prevalent. The new systems are defined as closed, regenerative, resource sparing, or sustainable production programs. Reference is made to organic, natural, biological, ecological, eco-, and cyclic farming or gardening. One challenge will be to maintain the current high producing, resource intensive systems while seeking alternative resource sparing production technologies. The magnitude of resource inputs - fertilizers, pesticides, land, water, mechanization, and human capital - is under review.

Table 7. Some emerging technologies for vegetable production.

1. Tissue culture of explants for propagation and seed production.
2. Conservation tillage and allelopathic response of plant residues.
3. Liquid and gel seeding for uniform stands, reduced costs, and earlier crop germination.
4. More efficient fertilizer and water utilization - drip irrigation, mycorrhizal relationships, biological nitrogen fixation, efficient cultivars.
5. Seed production of biennials in temperate climates.
6. New crops and intercropping combinations for increasing productivity and cropping index.
7. Protected cultivation - plastic covers for extending cropping season, stability, and magnitude of production.
8. Integrated pest management for pest control with lower costs, fewer environmental hazards, and greater food safety.
9. On farm computers for improved management decisions, programming of critical operations, and information tranfer.
10. Nutrient film and rockwool growing techniques in greenhouse culture.

Conversely, traditional production systems are under attack for being wasteful, exploitative of resources, and environmentally dangerous due to the excessive use of chemical fertilizers and pesticides. Losses of top soil from soil erosion, overdrafts of ground water, runoff, and the oxidation of organic matter from current agricultural practices are mounting and receiving increased attention. The challenge will be to develop integrated resource-efficient production and marketing systems that maximize both the stability and the magnitude of production over a wide marketing period, while maintaining optimal output and quality at minimal cost.

Seed Production and Propagation

A particularly important challenge for the future lies in technologies for high quality seed production and other methods of propagating vegetable crops. Progress has already been made with cauliflower, celery, cabbage, Chinese cabbage, and carrots. There was a special problem, for example, in selecting superior carrot roots and subsequently salvaging and reproducing the plants for seed production. This can now be overcome with carrots and some other crops by tissue culture (Table 5), which may be easier than developing lines that are capable of producing seed.

New Crops and Intercrops

New or little known vegetable crops will offer intriguing challenges, especially as they might be grown as intercrops and in combinations to increase productivity and the cropping index (Table 4). Interest in new crops stems from possibilities for increasing the food supply, improving food quality, and increasing opportunities for the producer (36). There is much to be gained from inventories of crops and practices in mainland China, Taiwan, and Japan, and from Latin American and African countries. In mainland China, as many as four crops may be grown simultaneously on the same site and separated at the harvest (28, 46). Wild germplasm and local varieties in developing countries must be protected from extinction and from international seed companies that monopolize germplasm and sell hybrids at high prices in their centers of genetic origin.

Protected Cultivation - The Plastic Revolution

No technological development has modified the course of controlled-environment vegetable production as much as the development of plastic films. They are now used extensively for covering old glass greenhouses and for constructing new greenhouses, air bubble inflated houses, solar greenhouses, and solar stills. Plastic covered structures can also be used to contain carbon dioxide for enhancing the growth of greenhouse crops.

Plastic films are similarly employed for covering crop rows and seed beds, and for soil mulches (14,15,21,22,45). Plastic tubes, laterals, and drip lines are important components of drip irrigation systems. They are used for packaging and maintaining controlled atmospheres for the prolonged storage of many different kinds of vegetables. Recent introductions of peat modules, rock wool, and nutrient film techniques for plant growing all involve plastic films for precise control of all aspects of the root environment (44). The nonvariable root environment for field tomato production in Florida is a good example (10). New developments in these and related areas were covered by special reports at the 21st International Horticultural Congress (51).

The modern day plastic revolution for vegetable crops is manifest in the precipitous rise and expansion of cultivated areas under plastic greenhouses, tunnels, row covers, and mulches. Japan and the countries in Western Europe are leaders in this technology (17). In 1981, there were 55,000 acres of plastic mulches and 30,000 acres of plastic greenhouses in mainland China, all constructed since 1979 and used almost exclusively for vegetable crop production. In each successive year since 1979, the use of plastic has increased ten-fold. Plastic covers and mulches are used for increasing yields, improving stability, and extending the season for many vegetables, including tomatoes, cucumbers, peppers, eggplant, cabbage, melons, and peanuts.

New developments in the use of plastics for vegetable production will occur in the decades ahead. They will include the use of films with white or silver stripes to repel insects. Biodegradable plastic soil mulches are also becoming available. Plastics are essential components for nutrient film hydroponic technologies and for drip irrigation systems. Plastic films and covers will extend and push vegetable production to new geographical frontiers in both agriculturally developed and less developed nations (14,21). Their use will characterize much of the vegetable production in the 21st century.

Carbon Dioxide and Plant Growth

The rising level of atmospheric carbon dioxide may have profound effects on vegetable production in the 21st century and beyond (27). Favorable effects of elevated levels of atmospheric CO_2 have long been demonstrated for the greenhouse culture of vegetable crops. Most respond to higher than the normal current atmospheric level of 340 ppm. There is a surge of interest in the direct biological effects of a rising level of atmospheric CO_2, since there is now an annual increase of 2 parts per million on a global scale (49). Extensive reviews of the effects of elevated levels of atmospheric CO_2 on plants indicate a potential for improved photosynthesis and yield, greater biological nitrogen fixation and mycorrhizal activity, enhanced water use efficiency, greater resilience to stresses of water, light, and temperature, and increased protection against air pollutants (19).

Conclusions

Opportunities for the improvement of vegetables, which constitute half the world's crops, reside in conventional plant breeding and the non-conventional genetic engineering and tissue culture pathways. Among the frontiers for science and technology will be the development of greater resilience to environmental and biological stresses. Integrated pest management, drip irrigation, protected cultivation under plastics, and conservation tillage will be among the important technologies for the future. Soil microbiological transformations will be within the cutting edge for significant scientific achievements in biological nitrogen fixation and rhizosphere associations. There will be alternative production systems and improvements in photosynthetic efficiency, nutrient uptake, seedling survival, and propagation for seed production. The biological effects of the currently rising level of atmospheric carbon dioxide should be monitored for species specificity and impacts on productivity, quality of products, and resilience to the environmental stresses of light, water, temperature, and air pollutants.

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