World-wide Use of Plastics in Horticultural Production

Sylvan H. Wittwer¹

No technological development has modified so much the course of controlled environment agriculture in the production of fruits, vegetables, flowers, and ornamentals as the recent widespread use of plastic films and related materials. Plastic films are used extensively for the design and covering of new greenhouses; the covering of old conventional glass greenhouses; for air-inflated, self-contained, or supported bubble houses; as interior curtains and external barriers to reduce heat loss in conventional greenhouses; and for the containment of CO₂-enriched atmospheres. Plastic films also are used for constructing high and low tunnels or covers for many row crops, protective covering of seed beds, and for soil mulches. Plastic tubes, laterals, and drip lines are important components of drip irrigation systems for high-value horticultural crops, which now cover 300,000 ha world-wide. Drip irrigation is often a component with plastic soil mulches, crop rowcovers, and plastic greenhouses. Recent introductions using plastic films include peat modules, bag cultures, rockwool, the nutrient-film technique, and nonvariable root environments for field-grown tomatoes (Geraldson, 1982; Wittwer, 1981). Flats, pots, and even labels for growing plants in greenhouses involve plastics. Plastic components contribute to the precise control of top and root environments of plants. In many modern greenhouses, all plant growing structures, other than the root media itself, are plastic (Fig. 1).

Department of Horticulture, Plant and Soil Science Bldg., Michigan State University, East Lansing MI 48824-1324.

¹*Professor Emeritus.*

The modern-day plastic revolution for horticulture is manifest in the precipitous rise and expansion of cultivated areas during the past 2 decades under plastic greenhouses, row tunnels, rowcovers, and soil mulches.

The most intensive crop-producing systems are those in greenhouses or other protective structures, and the most widely used protective structures world-wide are now predominately plastic. The end product is stable and extended crop productivity-at high levels. Plastic films of various composition, types, and structural designs help circumvent most of the hazards of climate and weather. Among the greatest constraints in crop production are adverse temperatures; moisture and light deficiencies; destructive winds, rains, snow and hail; the growth of weeds; deficiencies in soil nutrients; and atmospheric CO₂. With plastic film covers or mulches, near-optimal conditions of temperature, moisture, nutrients, air movement, and atmospheric composition are possible. One of the most sophisticated is the nutrient film technique (NFT), which employs a variety of plastic structures, films, and materials (Fig. 2). NFT is promotive of plant growth to near-optimal levels if combined with or enclosed in a plastic greenhouse. It offers the potential of maximizing control of both the top and root environments and optimizing both water and nutrient uptake (Cooper, 1976; Rudd-Jones, 1977; Spensley et al., 1978).

On the negative side, plasticulture needs financial capital, intensive management, and extensive resources, including human capital. It is a labor-intensive production system. Disposal of used plastic in ways that are environmentally friendly is also a challenge.

Significant developments in the production of horticultural crops linked with new technologies and the most efficient uses of resources are occurring world-wide in the current plastic revolution. Plastics provide an intensified expansion in both the vertical and horizontal dimensions for high-value crops (vegetables, cut flowers, fruit, bedding plants, potted plants, nursery stock, ornamentals). The technology is especially appealing in China, Japan, the Netherlands, Israel, and Egypt, where population densities are high, constraints of land and water resources are serious, and where the climatic endowments are most favorable for plasticulture, such as in southern and northwestern Europe, the Mediterranean countries, and the Near East. The potential is equally good for advanced as well as agriculturally developing countries. Plastic greenhouses, high tunnels, low tunnels, row covers, and plastic soil mulches now can be observed from the equator to the Arctic and Antarctic regions. One may well ask how it all began.

Historical and Current Perspectives

The early post-World War II period witnessed the first introduction of plastic sheeting for greenhouses, rowcovers, and soil mulches in the production of high-value horticultural crops. Until then, the basic glass greenhouse structure had not changed greatly in almost a century (Dalrymple, 1973).

Plastic greenhouses and high tunnels

The late Emory M. Emmert, of the Univ. of Kentucky, played a key role in the development of the plastic greenhouse in the United States. Because he could not afford a glass greenhouse, he designed crude wooden structures over which he placed wooden frames covered with stretched cellophane supported by wires. Emmert's plastic houses resembled the early glass greenhouses built out of sashes. He grew commercial crops of lettuce, tomatoes, cucumbers, and bedding plants in such structures for several years. When polyethylene became available, he used it for a small, privately owned range. The first plastic greenhouse was constructed at the Kentucky Agricultural Experiment Station in Winter 1953-54. It was still functional in 1959 (Fig. 3). The drive for the plastic greenhouse was its low cost (Emmert, 1955). Greenhouses in 1992 in the United States occupied slightly more than 5000 ha, four-fifths of which were either plastic or fiberglass, used primarily for bedding plants, potted plants, cut flowers, ornamentals, and a few vegetable crops (tomatoes, cucumbers, and leaf lettuce).

In Europe, the first experiments involving plastic for horticultural crops were reported in 1945 (Dalrymple, 1973). Polyethy-

“Significant developments in the production of horticultural crops linked with new technologies and the most efficient uses of resources are occurring world-wide in the current plastic revolution.”

Fig. 1. A modern greenhouse with plastic throughout for growing bedding and potted plants.

Fig. 2. *The nutrient film technique (NFT).* (Courtesy D. Rudd-Jones, Glasshouse Crops Research Inst., Littlehampton, England.)

lene was used in the early 1950s in Scandinavia to line the inside of glass greenhouses or to form overhead curtains to reduce heat loss (for which it is still used). The first polyethylene-covered greenhouse in the United Kingdom was erected in Nov. 1955. Growth in the use of plastic in Europe and elsewhere was slow throughout the 1950s and early 1960s. It was not until the mid- to late-1960s and during the 1970s that widespread use of plastics for greenhouse construction began in Russia, southern Europe, the Mediterranean area, and the Orient. Italy (Tesi, 1989; F. Tognoni, personal communication) and Spain had their first plastic houses by the early 1960s (Castilla, 1991), and Greece by 1966 (Olympios, 1991). Meanwhile, in Israel, plastic covers for crops were introduced in the late 1950s. Israel had extensive areas of high-value horticultural crops under plastic tunnels, rowcovers, and plastic soil mulches by 1971, paralleling the development and use of drip or trickle irriga-

Fig. 3. *The late Dr. Emory M. Emmert, father of agricultural plastics in America.* (photographed at the Univ. of Kentucky, May 1959.)

tion (Wittwer, 1971). China began using plastic film covers to protect rice seedbeds from the adversities of cold, windy spring weather in the central and southern provinces in 1958. There was widespread use in both China and Japan by 1965, and rapid expansion through the 1970s in China, Japan, and Korea. By 1980, there were 8600 ha of plastic greenhouses in Japan (Lawson, 1981); and, by 1984, 16,000 ha in China (Wittwer et al., 1987).

Beginning in the 1970s, the Mediterranean and Middle Eastern countries of Spain, Italy, Greece, Algeria, Portugal, Turkey, Jordan, and those countries bordering the Arabian gulf (Fontes, 1973; Hodges, 1981; Jensen, 1977) became prominent in the construction of plastic greenhouses and in the production and marketing of high-value greenhouse-grown crops. It was not until 1980, however, that the first plastic greenhouses were constructed in Egypt, following a research project financed by the World Bank (Wittwer, 1986). The use of plastic greenhouses for horticultural crops in Australia, New Zealand, Chile, Argentina, and South Africa paralleled those in the United States.

Many problems arose with the early commercial adoption of plastic greenhouses in the United States and elsewhere, which slowed progress in their use (Cotter and Chaplin, 1967; Dalrymple, 1973; Wittwer, 1963). There were problems of ventilation and heating. To retain the early advantage of low construction cost, inexpensive methods had to be found. Single layers of plastic covering were not as effective as glass in reducing heat loss. There was also excessive condensation underneath the plastic, which led to reduced and diffused light transmission and often greater disease problems. Two layers of plastic, with an air space in between, partly solved this problem and resulted in a 30% to 40% savings in fuel. Plastic used in the early houses also had to be replaced every year because of poor durability and deterioration induced by the sun's ultraviolet rays (Dhillon and Kirschling; 1971; Moore, 1972; Shales and Massey, 1968).

Plastic rowcovers or low tunnels and soil mulches

Rowcovers for high-value field-grown vegetable crops did not originate with the introduction of plastic. The use of parchment paper for covering early spring plantings of celery for protection against wind, cold rains, and frost in the Grand Rapids and Kalamazoo areas of Michigan preceded plastic use by more than 50 years (Wittwer and Lucas, 1956).

Much of the early history on the rise of agricultural plastic in the United States is given by Wells and Loy (1985a, 1985b) and

elsewhere by Dubois (1978) and Spice (1959). Again, the pioneering work on plastic rowcovers and soil mulches dates back to Emmett (1957). He simultaneously researched and promoted plastic greenhouses, rowcovers, and soil mulches. His work was followed by Shadbolt and McCoy (1960), who established the merits of rowcovers over hot tents, and Hall and Besemer (1972), who commercialized the use of plastic rowcovers for tomatoes, cucumbers, and peppers in San Diego County, Calif., where they became a standard practice. Plastic soil mulches were first used for strawberries in California in 1958 (Voth and Bringhurst, 1959). Muskmelons also were found to be very responsive to both black polyethylene soil mulches and rowcovers in New Hampshire (Wells and Loy, 1985a, 1985b) and Michigan (Carolus and Downes, 1958). These uses soon became standard practice on muskmelons (Bonanno and Lamont, 1980; Motsenbocker and Bonanno, 1989). This crop is sensitive to low soil and air temperatures and to wind damage, but tolerant to high temperatures.

These early introductions were followed by covers that were perforated, or slitted, and "floating" rowcovers of spunbonded polypropylene (Dubois, 1978; Wells and Loy, 1985b). The latter are very light in weight, applied loosely over the row, and require no wire hoops for support (Fig. 4). In the United States and Canada, and in many other countries, particularly in the Mediterranean area, rows of high-value horticultural crops (strawberries, muskmelons, watermelons, cucumbers, tomatoes) are covered with wire-supported tunnels of plastic, in combination with black polyethylene mulch. The two are frequently combined with drip irrigation. Plastic rowcovers and soil mulches have even a wider geographical distribution, cover more extensive land areas, and have a greater spectrum of uses in the production of high-value crops than do plastic greenhouses (Hopen, 1965; Makus and Gonzalez, 1991; Marr et al., 1991; Nerd et al., 1989; Pritts et al., 1992; Stevenson et al., 1986).

Current Global Status of Plasticulture for Horticultural Crops

Geographically, plastic covers and mulches may be found in every state in the United States, including Hawaii and Alaska; and in all Canadian provinces, including the maritimes. They are found in all countries of western, northern, eastern, and southern Europe, as well as North Africa. Included are the British Isles, and especially the Isle of Guernsey; Scandinavia; the Baltic States;

Fig. 4. Plastic covers for rice seed-beds in Japan, one of the most extensive uses for plastic in the Orient.

Russia; all nations bordering the Mediterranean, including Spain, with the Canary Islands, Algeria, Agadir of Morocco, Malta, and especially Italy and Greece; and with the Isle of Crete, and Egypt. Moving to the Orient, plasticulture can be seen throughout all the provinces of China, Japan, and Korea, and in some of the higher elevations in the Philippines and near Chiang Mai in Thailand. In the southern hemisphere, it may be seen near metropolitan areas in Australia, New Zealand, Chile, Argentina, and South Africa.

Plasticulture is often very localized. At present, the heaviest concentrations in the use of plastic as plant-growing structures and as films in the United States are in southern California, especially San Diego County; the Grand Rapids, Kalamazoo, and Monroe areas of Michigan; Cleveland, Ohio; and southern New Jersey. Rather extensive, but local, use may also be seen in New Hampshire, New York, Arizona, Texas, Pennsylvania, and North Carolina. The Leamington, Vineland, and Toronto areas of Ontario, Canada are most concentrated. In Europe, there are plantings using plasticulture in Denmark and Holland, and vast areas in the Almeria Valley and Canary Islands of Spain, and in Portugal, Italy, and Greece, including the Island of Crete. There are also extensive areas throughout the United Kingdom, especially the Isle of Guernsey; around Moscow and St. Petersburg in Russia; throughout Israel, in Jordan, the Adana and Tarsus regions of Turkey, and, more recently, the desert bordering "new lands" areas of Egypt, especially in the vicinity of Cairo. In the Far East, plasticulture may be seen throughout Japan, which has the highest intensity of arable land covered with plastic of any major nation on earth. Japan's area of plasticulture is exceeded only in China,

"Plasticulture is often very localized."

which is now the world's number-one user of plastic for crop production. Areas of special concentration are found in the municipalities of Beijing, Tianjin, and Shanghai, and near the major cities of Harbin, Nanjing, and Hangzhou.

Table 1 gives summaries of the approximate world-wide distribution of plastic greenhouses and high tunnels by country for the primary crops produced. Table 2 lists some countries where low tunnels or rowcovers and plastic film soil mulches are now used extensively, and the major crops produced. The rowcovers and soil mulches may be used singly or in combination. They often are combined with drip irrigation systems.

Plasticulture in China

In China, plastic covers were first used in 1958 on rice seed-beds in early spring to accelerate growth and speed up the dates for transplanting by 10 days to 2 weeks. By the mid 1960s and early 1970s, this was a standard practice, as it also was in Japan (Fig. 4). In June 1977, it was observed that, adjacent to some of the major cities (Beijing, Shanghai, Nanjing, Xian, and Yangzhou), there were >1000 ha of greenhouses of single-layer polyethylene plastic. This compared with 60 ha of glass greenhouse structures. Plastic tents were used to protect high-value crops from

rain in southern China (Plucknett and Beemer, 1981).

Plastic-film mulching of crops began in 1977 with a mere 50 ha. This was followed by an exponential growth in the use of plastic films for mulching during the next 4 years, as seen below (Wittwer et al., 1987).

Year	Hectares
1979	50
1980	2,000
1981	20,000
1982	200,000
1983	2,000,000

Stabilization occurred at slightly more than 2 million ha from 1983 through 1992. The crops to which plastic mulches are applied are cotton, watermelon, peanuts, rice seed beds, corn (including some sweet corn), tobacco, some 25 different vegetable crops, and strawberries.

As of Sept. 1992, there were two kinds of plastic-covered greenhouses in China. The so-called solar greenhouse, or "lean to," has a brick wall on the north side and a plastic cover extending from the top of the north wall to a somewhat lower plastic-covered or brick wall on the south side. About 12,000 ha are covered with such structures.

The second type of plastic greenhouse is the plastic-film shed or tunnel. These comprise a total of 50,000 ha and are seen over extensive land areas around all major cities such as Beijing, Shanghai, Tianjin, Nanjing, Harbin, and Yangzhou, especially in central and northern China (Fig. 5).

Many plastic greenhouses are continuous spans covering several hectares, others are separated by 3 to 6 feet with rows of vegetable crops in between. Individual houses cover an area of 600 m². They may be heated or unheated. The plastic usually is removed during the summer or the crops simply are allowed to grow through and out of the plastic. Plastic covers are replaced annually, with the growing season usually extending from October to June. Soil enriched with animal manures or compost is the usual growing medium, but the nutrient-film technique and other artificial growing media or soil mixes are being introduced. Many vegetable crops are grown within these structures, along with strawberries, and sometimes grapes. They include cucumber, tomato, eggplant, sweet pepper, hot pepper, melon, green bean—both bush and pole, Chinese cabbage, gourds of many kinds, green onion, the Chinese chive, leek, stem lettuce, broad bean, celery, Swiss chard, and ordinary cabbage. Production is under the "individual contract responsibility system" and marketing and distribution through the "market economy system."

Table 1. *Estimates of plastic greenhouses and high tunnels with major crops.*

Country	Hectares	Crops (in approximate order of importance)
China	62,000	Cucumber, tomato, strawberry, pepper, eggplant, onion, chives, green bean, chinese cabbage, gourd.
Japan	30,000	Cucumber, tomato, cut flowers, strawberry, melon.
Spain	24,000	Watermelon, cut flowers, pepper, melon, strawberry, tomato, cucumber, squash.
Italy	21,000	Tomato, strawberry, pepper, melon, cucumber.
Greece	11,000	Tomato, cucumber, melon, pepper, eggplant, cut flowers.
Algeria	10,000	Tomato, cucumber, melon.
France	6,000	Tomato, cucumber, strawberry.
Egypt	6,000	Tomato, cucumber, melon, cut flowers.
Portugal	5,000	Melon, strawberry, tomato, pepper.
South Korea	4,000	Cucumber, tomato, green bean, cabbage.
Morocco	3,400	Tomato, cucumber, pepper, eggplant.
Turkey	3,000	Tomato, cucumber, melon, eggplant, pepper.
Russia	3,000	Cucumber, onion, tomato, strawberry.
United Kingdom, Holland, Belgium, Scandinavia, and Germany	6,000	Tomato, cucumber, cut flowers, grape, lettuce, strawberry.
United States	3,500	Bedding plants, potted plants, foliage plants, cut flowers, vegetables.
Canada	500	Bedding plants, potted plants, cut flowers, vegetables, cucumber, tomato.
Israel	300	Cut flowers (roses, carnations), tomato, strawberry.

Both production and marketing are private operations. (Wittwer et al., 1987).

Plasticulture in Greece

In Greece, low tunnels (rowcovers) were first used in 1967. At that time, there were 300 ha. The first plastic greenhouses were constructed in Winter 1955-56, with an area of only 0.2 ha. By 1973, there were 600 ha of tunnels and 1300 ha of greenhouses. The 1990 producing areas covered 4000 ha with plastic greenhouses, and about 7500 ha with rowcovers and soil mulching. Most of the greenhouses are in areas where crops can be produced without or with minimum heating requirements.

The principal crops for greenhouses are the tomato and cucumber. There are also some plantings of pepper, eggplant, green beans, and cut flowers. Watermelon, muskmelon, strawberry, squash, and tomato are the principal crops under low tunnels or rowcovers and mulching. Watermelons and muskmelons comprise 90% of the total. Only 19% of the vegetables are grown in heated greenhouses, while 57% of the ornamentals and flowers are grown with heat. Vegetables are grown in >90% of the greenhouses, with <10% for flowers and ornamentals. The island of Crete produces one-third of all greenhouse-grown tomatoes, half the cucumbers, and most all of the muskmelons of Greece (Olympios, 1991).

Plasticulture in Egypt

Plasticulture in Egypt began in 1980, with <1 ha of plastic greenhouses. This expanded to 100 ha in 1982. By 1985, there were 250 ha. A special FAO/UNDP mission was assigned in Jan. 1986 to explore further possibilities, and a National Workshop on Protected Agriculture was held in Cairo in Dec. 1986 (Wittwer, 1986). Egypt, with very limited land and water resources but abundant human resources, a relatively frost-free climate, a near cloud-proof atmosphere, low humidity for evaporative cooling, abundant sunlight, moderate temperatures throughout most of the year, and a ready market was viewed as having great potential in plasticulture using greenhouses, rowcovers, and soil mulches (Sirjacobs et al., 1988).

Today (1992) there are 6000 ha of plastic greenhouses, all recently constructed, and perhaps 3000 ha of plastic rowcovers and soil-mulched areas (Tables 1 and 2). Crops include the strawberry (with harvests from November to May), tomato, cucumber, pepper, eggplant, melon, squash, and cut flowers. There are extensive plantings of melons and strawberries with soil mulches and protected rowcovers (Fig. 6). Production areas are along the Nile River, near and in Cairo,

Table 2. *Plastic rowcovers (low tunnels) and soil mulches (singly or in combination) and the crops grown.*

Country	Hectares	Crops in approximate order of importance
China	500,000	Watermelon, cucumber, tomato, strawberry, melon, squash.
Spain	70,000	Watermelon, pepper, melon, strawberry, green bean, eggplant, tomato, cucumber, squash.
Japan	25,000	Strawberry, tomato, cucumber, melon.
United States	25,000	Strawberry, melon, tomato, pepper, cucumber.
Italy	16,000	Strawberry, melon, tomato, watermelon, squash, cucumber, eggplant.
Greece	7,500	Watermelon, melon, squash, strawberry, tomato.
Israel	4,000	Strawberry, tomato, cucumber, flowers.
Turkey	4,000	Melon, strawberry, tomato.
South Korea	3,000	Cucumber, tomato, watermelon.
Egypt	3,000	Melon, tomato, strawberry, cucumber.
Tunisia	1,200	Tomato, watermelon, strawberry, cucumber

the "new lands" bordering the delta, and those in the near-desert areas in the upper Nile valley.

Uses for Specific Crops

Strawberries. World-wide, the most extensively grown crop with the aid of plastic film (greenhouses, tunnels, rowcovers, or soil mulches) is the strawberry. Production is from October to May in California, Japan, China, Israel, Egypt, and throughout Europe-especially in the Mediterranean area. Strawberries may be grown in greenhouses, under rowcovers, with plastic mulches, or a combination of the three along with drip irrigation. All-season varieties, first developed in California, are found throughout the world (Voth and Bringham, 1959), along with plastic mulching and rowcovers. Plastic mulches were first used in California in 1958. There are 8000 ha of strawberries in California that are mulched with clear polyethylene plastic (Fig. 7). The mulch is applied very snugly

Fig. 5. A typical modern plastic greenhouse in the Shanghai Municipality of China, Sept. 1992.

Fig. 6. Rowcovers (low tunnels) for muskmelons in the "new lands" of Egypt, Dec. 1986.

over the soil surface as soon as possible after transplanting. Associated with high soil temperature is a 50% increase in total yield and double the early yield. Drip irrigation, introduced in 1957, is used with the plastic (Voth and Bringhurst, 1990).

Plasticulture for strawberries with suitable varieties is used for winter production, either in the open or in greenhouses throughout the northern hemisphere. Rowcovers along with the plastic mulches were next introduced in the Mediterranean countries and in China and Japan.

Cucumbers. The cucumber also is well-adapted to growth in plastic greenhouses and tunnels. Cucumbers rank first for culture in plastic greenhouses in Japan, China (Fig. 8), Korea, and Russia, and is second only to tomatoes in Greece. Different varieties are grown throughout all European countries, especially those in the eastern and northern parts. Production is high, the crop matures

Fig. 7. Plastic soil mulching of strawberries in San Diego County, Calif., Feb. 1978.

earlier and is less exacting than the tomato in cultural requirements, and production may be carried through winter months. Two crops a year may be grown in many countries bordering the Mediterranean. Aside from growth in greenhouses, cucumbers are highly productive under rowcovers and with plastic soil mulches.

Muskmelons and watermelons. Melons are among the most responsive of all crops to plasticulture. They are sensitive to both low soil and air temperatures and to wind, but are very tolerant to high temperatures. With perforated or slitted rowcovers and spunbonded floating rowcovers, there is some frost protection (Wells and Loy, 1985b). Both watermelons (5000 ha) and muskmelons (1500 ha) are grown under rowcovers in Greece and, to a lesser extent, in greenhouses. Watermelons and muskmelons are two of the leading crops for row tunnels in Spain and Portugal. Melons are grown in the greenhouses of Japan, China, and in most northwestern European countries, as well as those near the Mediterranean. Rowcovers and black plastic soil mulches are seen in Egypt and Israel and in dispersed areas of the northern United States and Canada. Early, as well as total, yields may be increased for muskmelons. The use of black plastic mulches, often coupled with transparent or slightly opaque rowcovers, is common in California, Arizona, Michigan, New York, New Jersey, and Essex County, Ont., Canada.

Watermelons in China are especially responsive to clear plastic soil mulching (Wittwer et al., 1987). They are grown extensively in all provinces, autonomous regions, and municipalities. The progressive use of plastic soil mulches for watermelons in China is given below.

<u>Year</u>	<u>Hectares</u>
1980	200
1982	4,820
1984	58,660
1986	319,533

At present, 360,000 ha of watermelons are mulched with plastic annually in China. This accounts for 18% of the 2 million ha of mulched crops, being exceeded only by cotton and equal to that for peanuts. In the northern, northeastern, and northwestern regions of China, 75% of the total watermelon area is mulched with plastic. There is also an increase in the use of plastic rowcovers combined with the soil mulches. Transparent soil mulches increase soil temperatures and prevent surface evaporation of soil moisture (Fig. 9). With plastic, the melons in northern China mature 20 days earlier, and are the main source of supply for all of China during

late August and through September. In southern China, the plastic mulch reduces soil erosion and prevents compaction from heavy rains. The mulch promotes the growth and fruiting of watermelons and increases total yields by 29% to 30% (Runfang, 1990).

Plastic tunnels often are combined with plastic mulch. This is the most popular method of forcing culture in watermelon production. Such a "double layer" of film cover is used widely in northern China and Korea to take advantage of sunny spring weather for early maturity and to give wind and frost protection. In the lower reaches of the Yangxi river valley and the suburbs of Shanghai, the growing of watermelons in plastic tunnels promotes early fruit set, early maturity, and results in enormously high yields.

Watermelon production in small to medium-sized plastic houses has progressed rapidly in central China. The structures are simple, with flexible bamboo frames (Fig. 10). Sometimes a tunnel with mulch is prepared within the plastic house (Fig. 11) to increase warmth. This results in a "three-layer" film cover. The area of tunnels and plastic houses in Tongshan County of Jiangsu Province now totals 1800 ha (Runfang, 1990).

Bedding plants, potted plants, cut flowers, and vegetable crops in the United States

There are 12,500 acres (5100 ha) of greenhouses in the United States, two-thirds of which are now plastic and four-fifths either plastic or fiberglass (USDA, 1988). As late as the 1960s and early 1970s (Wittwer and Homna, 1979), there were 1000 acres (405 ha) devoted to vegetables (primarily, tomato, cucumber, and lettuce). That acreage has diminished to 250 acres or less, although there are still large plantings in Ohio and California, with small plantings in Pennsylvania, New York, Michigan, Florida, and a few other states, a part of which are relatively small hydroponic units. Bedding plants predominate as crops grown in plastic structures. Of total production, 10% to 20% are vegetables, and the balance flowers. Bedding plants are, in turn, followed in importance by potted plants (see Fig. 1), cut flowers, foliage plants, nursery crops, and vegetables. Vegetables make up scarcely more than 5% of the total greenhouse production in the United States (USDA, 1988). Cut flowers and potted plants, with about two-thirds grown in plastic greenhouses, are making inroads into what has been almost exclusively traditional greenhouse vegetable production in Canada, northern Europe, Japan, the Mediterranean countries, and, more recently, in China and Korea.

In no country, however, has the transi-

Fig. 8. *The cucumber is the most widely grown of all vegetables in the plastic greenhouses of the Orient.*

Fig. 9. *Transparent soil mulches for watermelons in northeast China near Harbin, May 1985.*

Fig. 10. *A medium-sized plastic house in China with flexible bamboo frames.*

Fig. 11. A low plastic tunnel inside a high plastic tunnel to give added protection for tender crops in early spring.

tion from vegetables to flowers been so dramatic as in the United States. Southern California, along with New York, Pennsylvania, Ohio, and the Grand Rapids and Kalamazoo areas of Michigan have the most-concentrated areas for plasticulture of bedding and potted plants. In Michigan, it is an industry that rose from celery fields. The small glass greenhouses where celery transplants were grown formerly have been replaced by larger and more-efficient plastic structures designed specifically for bedding plants. In Michigan, Ohio, New York, and Pennsylvania there are nearly 500 plastic greenhouse farms in each state. These states, along with California, probably represent the largest concentrations in the world of bedding plants grown in plastic greenhouses.

Some novel uses of plastic mulches and covers

Seed yam production in Nigeria is enhanced greatly by the use of polyethylene

mulch. It makes staking unnecessary, controls weeds, reduces soil erosion, preserves soil moisture, maintains a desirable soil temperature for good plant growth and development, ensures a good stand, and shortens the period during which the land is occupied in seed production. The mulch covers the planting ridges and a part of the furrow between ridges (Fig. 12). Soil on the edges holds down the plastic and holes are cut in the plastic for setting the plants (Asnani et al., 1985).

Plantings for sweetpotatoes are mulched in a similar manner for weed control, reduction in soil erosion, and preservation of soil moisture. Related to the sweetpotato in the beneficial responses to plastic soil mulches is cassava. Plastic soil mulches ensure good plant establishment (up to 95%) and vigorous plant growth. Weeding is greatly reduced, soil erosion held to a minimum, and soil moisture is conserved. There is less mealy bug and spider mite infestation because of an improved moisture regime. Plastic mulches are low in cost, easy to use, and economical (IITA, 1984).

Sweetpotato plant beds, covered with clear plastic produce a greater number and weight of transplants. Early harvest of transplants is accelerated by 8 to 12 days (Porter, 1991).

The benefits of earlier maturity from plastic mulching of sweet corn, demonstrated by Hopen (1965), has since been adopted elsewhere. It was reported in 1979 that, in France, up to 5000 ha of field corn were mulched with clear plastic. Yields were doubled and harvest advanced by 3 to 4 weeks (Wittwer, 1981). It appears that, with clear plastic, corn production may be moved 400 miles further north or into mountain areas with greater elevations. This is precisely the case where sweet corn is produced as far north as Alaska, and production has been moved to high mountain areas in southern China.

Opaque plastic rowcovers (Makus and Gonzales, 1991) allow the production of white asparagus without mounding of beds. The plastic also protects against short durations of frosts and produces higher trimmed weights. The asparagus requires less-frequent cutting.

Plastic covers are being introduced for tropical fruit production, both in the eastern and western hemispheres. Bunches of bananas are encased in colored plastic films as they approach field maturity (Fig. 13). The plastic offers protection from insects, birds, and other pests. The result is a product that is more attractive and of uniform maturity. Frames of clear plastic encircling young papaya plants give wind and insect protection and hasten early growth and fruit production (Fig. 14). High-quality, year-round produc-

Fig. 12. A polyethylene soil mulch replaces staking for seed yam production in Nigeria.

tion of tomatoes and cucumbers in plastic greenhouses constructed from native materials just a few kilometers from the equator near Nakuru, Kenya, provide fresh salads for an ever-increasing tourist trade in nearby Nairobi (Fig. 15).

Advantages of Plasticulture

The initial driving forces for the use of plastics in horticulture were, first, to increase earliness and total crop productivity of high-value horticultural crops (Abdul-Baki and Spence, 1992); second, to take advantage of out-of-season production; and third, to use something as effective, but much less expensive, than glass as a protective covering. This latter advantage was the primary stimulus for Emmert's (1955) pioneering studies in Kentucky.

The promotion of earliness, coupled with more-productive and predictable total yields, holds for most all field-grown horticultural crops where plastics are used. The effectiveness of plastic covers in compensating for low soil temperatures and the reductions in wind damage has been phenomenal for vine crops, especially watermelon, muskmelon, squash, cucumber, sweet corn, strawberry, yam, and sweetpotato and cassava in the tropics. Harvest may be hastened by a few days, a week, or months, depending on the structures and the combinations of covers used. Earliness is especially important in the response to plastic covers for tomato, cucumber, pepper, eggplant, melon, sweet corn, and cut flowers. The improvement of cut flower quality is often a compelling factor for using plastic covers.

Extending the geographical areas for successful production applies to a wide range of vegetables, flowers, and fruit crops from the equator (Figs. 12 and 15) to the arctics (Fig. 9). Earlier maturity is promoted. Most successful has been the plastic greenhouse for cucumber, tomato, pepper, eggplant, strawberry, melon, green bean, and green onion; and for tomato, cucumber, melon, and sweet corn in the field. Modern greenhouses, constructed with double-layer plastic with an air space between, are more retentive of heat and CO_2 than are glass greenhouses. Protection against short-term frosts and cold waves with temperature depressions ranging from 1 to 3°C is possible in the open field with some types of spunbonded and floating rowcovers of polypropylene (Wells and Loy, 1985b; Fig. 16).

Other beneficial effects of plasticulture with row crop mulching and/or covers in the field are the conservation of water through reductions in surface evaporation; a reduction in the loss of soil nutrients by leaching

Fig. 13. Plastic covers are used in the tropics to encase bananas as they approach field maturity offering protection from pests and encouraging uniform ripening

Fig. 14. Box frames of clear plastic give wind and insect protection and hasten early growth and fruit production in papaya.

Fig. 15. Plastic greenhouse tomato production near Nakuru Kenya, July 1988.

Fig. 16. Spunbonded polypropylene, a floating rowcover requiring no wire support. (Courtesy Otho Wells, Univ. of New Hampshire.)

Fig. 17. Plastic soil mulches are combined with plastic rowcovers (low tunnels) and drip irrigation for strawberry production in Israel.

Fig. 18. Plastic bag culture, soil mulching, and drip irrigation for tomatoes grown in plastic greenhouse near Littlehampton, England.

(Wein and Minotti, 1987); weed control (especially important for vine crops); alleviation of soil compaction by the beating action of rain; protection of plants against wind, rain, hail, and insects; and an increase in atmospheric CO_2 . One, several, or all of the above advantages of plasticulture may accrue, depending on the crop, where it is grown, and the plastic structures employed.

In summary, plasticulture provides one of the few options for further expansion of both the horizontal and vertical dimensions of horticultural crop production and for the most-effective management and use of land, water, fertilizer, sunlight, and atmospheric CO_2 as essential crop inputs. There are also new vistas for marketing the improved quality virtues of fresh fruits, vegetables, and cut flowers.

Disadvantages of Plasticulture

Cost is a chief constraint in the use of plastics for horticultural crops. While rowcovers are intermediate in cost between plastic soil mulches and plastic greenhouses, they are seldom used alone. A usual combination with rowcovers is a plastic soil mulch and drip irrigation, as is used for strawberries in Israel (Fig. 17). In fact, drip irrigation often is combined with plastic soil mulching and plastic bag culture inside a plastic greenhouse, sometimes with the addition of rowcovers as well (Fig. 18). Each input requires an additional expenditure. A further cost, which must be factored in, is the annual or periodic replacement of plastic coverings for greenhouses.

Plastic culture demands high-production technology and significant human resource inputs. Those engaged in growing crops with the aid of plastic mulches, covers, or greenhouses should receive technical training as to factors controlling plant growth and the art of plant growing. Heating, ventilating, cooling, and condensation difficulties still exist with crops grown inside plastic enclosures. Programming inputs of mineral nutrients, and meeting optimal requirements for temperature, light, and atmospheric CO_2 levels are desirable and should be considered. Plasticulture involves a series of production technologies, beginning with plant growing through to harvest, that relate to one of the most intensive types of agricultural production coupled with the most efficient use of human and natural resources. It is also one of the most labor- and management-intensive agricultural production systems. The cost of labor along with the cost and availability of other inputs could be prohibitive.

A final problem is disposal of used plastic. Plastic pollution is unsightly and is recog-

nized as an environmental hazard and a constraint wherever plasticulture has flourished. A possible approach for the future is the use of photo- or biodegradable plastic (Fig. 19). Several products of biological origins have been introduced that show some promise. Degradability, however, has not been sought after for plastic greenhouse covers until recently. Durability has rather been the primary concern. Recycling agricultural plastics is another option for disposal. The presence of foreign particles is, however, an obstacle for reprocessing.

Future Prospects

There will be many new developments with plastics for controlled-environment agriculture. Plastics offer an option for both increased vertical and horizontal expansion in horticultural crop production and needed improvements in quality of the products grown. Use of plastic films will be extended during the next decade to many additional crops and in developing countries. Case histories for the past decade exist in China and Egypt. Plastic films with colored stripes and other color patterns may be developed that will help repel insects (Brown and Brown, 1992; Scott et al., 1989). Light- and biodegradable plastics ultimately will be fabricated to avoid undesirable residues, alleviate disposal problems, avoid "plastic pollution," and be more environmentally acceptable. Nutrient film technologies, first developed in the United Kingdom, for control of root as well as shoot environment will expand worldwide, as is occurring in China, Japan, and Egypt for both greenhouse and open-field production of fruits, vegetables, flowers, potted plants, and ornamentals.

Plastic tubing networks and emitters, combined with soil and plant covers of plastic, will facilitate further drip irrigation and refinements in controlled environment agriculture in China, Japan, Mexico, Australia, New Zealand, the Mediterranean area, and many developing countries world-wide. New developments also can be projected for bubble houses (Fig. 20) and solar still technologies for desert areas, and in the design of low-energy solar and conventional greenhouses.

The expanded use of plastic film covers for greenhouses and row crops and as soil mulches will continue and will push the productivity of high-value fruits, vegetables, flowers, and ornamentals into new geographical frontiers, including the tropics, in both agriculturally developed and less-developed nations, as has been witnessed recently for China, Korea, Egypt, and Nigeria. Plasticulture as a technology for enhancement of plant growth is not confined to the Western world.

Fig. 19. Photo-degradable plastic at the Horticultural Research Inst., Heilongjiang Province, China, Sept. 1992.

The phenomenal world-wide rise in the use of plastics during the past 2 decades, with particular focus on high-value horticultural crops, with the goals of earliness, increased productivity, and improved product quality, will result in farmers' learning new skills for enhancement of crop productivity and more-effective management of resources. Many such skills and technologies can be transferred to the production of crops in open fields. This will relate to improved fertilizer and water-use efficiency. Land areas not now suitable for traditional farming can be put to use. There will be new developments for integrated pest management, control of soil erosion, sustainable systems of soil management, the arts of successful modeling of plant growth, and unique methods of plant growing and propagation. There will be programming of harvests for meeting market demands of increasingly discerning consumers. Postharvest handling and new marketing and

Fig. 20. A self-inflated plastic bubble house in north-central Ohio used for winter vegetable production.

packaging skills will be needed. The results of research on crops grown under protection can be quantified easily as to returns on investments for improving crop yields and increased earnings.

Literature Cited

- Abdul-Baki, A. and C. Spence. 1992. Black polyethylene mulch doubled yield of fresh-market field tomatoes. *HortScience* 27(7):287-289.
- Asnani, V.L., J.A. Otoo, and S.K. Hahn. 1985. Seed yam production—an improved technology. Intl. Seminar on Modern Technol. for Agr. in Jamaica and the Caribbean. Kingston, Jamaica. Jan. 27-31 Jan. 1985. IITA, Ibaden, Nigeria.
- Bonanno, A.K., and W.J. Lamont. 1987. Effect of polyethylene mulches, irrigation method and row-covers on soil and air temperature and yield of muskmelon. *J. Amer. Soc. Hort. Sci.* 112(5):735-738.
- Brown, S.L. and J.E. Brown. 1992. Effect of plastic mulch color and insecticides on thrips populations and damage to tomato. *HortTechnology* 2(2): 208-211.
- Carolus, R.L. and L.S. Downes. 1958. *Studies* on muskmelon and tomato responses to polyethylene mulching. Mich. Agr. Expt. Sta. Quart. Bul. 40 (4):770-785.
- Castilla, D.N. 1991. Protected cultivation in Spain. *Colture Protette* 104-15.
- Cotter, D.J. and C.E. Chaplin. 1967. A review of plastic greenhouses: The problems, prospects and possibilities. *HortScience* 2(1):7-9.
- Cooper, A.J. 1976. Nutrient film technique of growing crops. Grower Books, London.
- Dalrymple, D.G. 1973. Controlled environment agriculture: A global review of greenhouse food production. Econ. Res. Serv., Washington, D.C. USDA Foreign Agr. Econ. Rpt. 89.
- Dhillon, P.S. and P.J. Kirschling. 1971. Profitability of tomato productions under plastic greenhouses. Rutgers Univ., A.E. 355.
- Dubois, P. 1978. Plastics in agriculture. Applied Science Publ., London.
- Emmert, E.M. 1955. Low-cost plastic greenhouses. Kentucky Agr. Expt. Sta. Prog. Rpt. 29.
- Emmert, E.M. 1957. Black polyethylene for mulching vegetables. *Proc. Amer. Soc. Hort. Sci.* 69:464-469.
- Fontes, M.R. 1973. Controlled environment horticulture in the Arabian Desert at Abu Dhabi. *HortScience* 8(1):13-16.
- Geraldson, C.M. 1982. Stabilization of the root environment with a high moisture level for maximum vegetable yields. 21st Intl. Hort. Congr. 29 Aug.-4 Sept. 1982 Hamburg, Germany.
- Hall, B.J. and S.T. Besemer. 1972. Agricultural plastics in California. *HortScience* 7(4):373-378.
- Hodges, C.N. 1981. New options for climatic-defensive food production, p. 181-205. In: L.E. Slater and S.K. Levin (eds.). *Strategies and technologies for climate-defensive food production*. Westview, Boulder, Colo.
- Hopen, H.J. 1965. Effects of black and transparent polyethylene mulches on soil temperatures, sweet corn growth and maturity in a cool growing season. *Proc. Amer. Soc. Hort. Sci.* 86:415-420.
- IITA. 1984. Root and tuber improvement program. Inst. of Trop. Agr., Ibaden, Nigeria.
- Jensen, M.H. (ed.). 1977. *Proc. Intl. Symp. on controlled environment agriculture*. 7-8 Apr. Environ. Res. Lab., Univ. of Arizona, Tucson.
- Lawson, G.E. 1981. Plasticulture in Japan. *Amer. Veg. Grower* 29 (10):14,20-21.
- Makus, D.J. and A.R. Gonzalez. 1991. Production and quality of white asparagus grown under opaque rowcovers. *HortScience* 26(4):374-377.
- Marr, C., W.J. Lamont, Jr., and M. Allison. 1991. Rowcovers improve seedless watermelon yields in an intensive vegetable production system. *HortTechnology* 1(1):103-104.
- Moore, E.L. 1972. Tomato varieties suited for greenhouse forcing. Mississippi Agr. Expt. Sta. Info. Sheet 768.
- Motsenbocker, C.E. and A.R. Bonanno. 1989. Rowcover effects on air and soil temperatures and yield of muskmelon. *HortScience* 24(4):601-603.
- Nerd, A., A. Karady, and Y. Mizrahi. 1989. Irrigation, fertilization, and polyethylene covers influence bud development in prickly pear. *HortScience* 24(5):373-375.
- Olympios, C.M. 1991. The situation of protected cultivation in Greece. *Plasticulture* 91(3):5-16.
- Plucknett, D.L. and H.L. Beemer, Jr. 1981. Vegetable farming systems in China. Westview, Boulder, Colo.
- Porter, W.C. 1991. Bed covers alter temporal distribution of production of sweetpotato transplants. *HortScience* 26(3):252-253.
- Pritts, M., K.A. Worden, and M. Eames-Sheavly. 1989. Row-cover material and time of application and removal affect ripening and yield of strawberries. *HortScience* 24:531-536.
- Rudd-Jones, D. 1977. Root environment control: Nutrient film culture. *Proc. Intl. Symp. on Controlled Environ. Agr.* p. 216-224.
- Runfang, X. 1990. Watermelon production and variety improvement in the Peoples Republic of China. Jiangsu Acad. Agr. Sci., Nanjing, China.
- Scott, S.J., P.J. McLeod, F.W. Montgomery, and C.A. Handler. 1989. Influences of reflective mulch on incidence of thrips (Thysanoptera: Thripidae: Phaeothripidae) in staked tomatoes. *J. Entomol. Sci.* 24 (4):422-427.
- Shadbolt, C.A. and O.D. McCoy. 1960. Temperature and plant responses to paper and plastic protectors on cantaloupes. *Hilgardia* 30:247-266.

- Shales, F.D. and P.H. Massey, Jr. 1968. Tomato production in plastic greenhouses. Virginia Polytech. Inst. Ext. Div. Publ. 154.
- Sirjacobs, M., A. Nisen, and Ch. von Zabletitz. 1988. Protected cultivation in the Mediterranean climate greenhouses in Egypt. United Nations Food & Agr. Org., Rome.
- Spensley, K., G.W. Winsor, and A.J. Cooper. 1978. Nutrient film technique-crop culture in flowing nutrient solution. Outlook Agr. 9:299-305.
- Spice, H.R. 1959. Polyethylene film in agriculture. Faber and Faber, London.
- Stevenson, D.S., G.H. Neilson, and A. Cornelsen. 1986. The effect of woven plastic mulch, herbicides, grass sod, and nitrogen on 'Foch' grapes under irrigation. HortScience 21(3):439-440.
- Tesi, R. 1989. Dipartimento of orloflorofriticoltura. Universita di Firenze Vin Donezelli, 6 (CP 50144). Firenze, Italia.
- U.S. Department of Agriculture. 1988. Census of horticultural specialties. Census of Agriculture, USDA, Washington, D.C.
- Voth, V. and R.S. Bringham. 1959. Polyethylene over strawberries. Calif. Agr. 13(5):5-14.
- Voth, V. and R.S. Bringham. 1990. Culture and physiological manipulation of California strawberries. HortScience 25(8):889-892.
- Wein, H.C. and P.L. Minotti. 1987. Growth, yield, and nutrient uptake of transplanted fresh-market tomatoes as affected by plastic mulch and initial nitrogen rate. J. Amer. Soc. Hort. Sci. 112(5):759-763.
- Wells, O.S. and J.B. Loy. 1985a. Rowcovers: A changing landscape. HortScience 20(5):800.
- Wells, O.S. and J.B. Loy. 1985b. Intensive vegetable production with rowcovers. HortScience 20(5):822-826.
- Wittwer, S.H. 1963. Tomato production in plastic greenhouses-opportunity with problems. Proc. 1963 Agr. Plastics Conf.
- Wittwer, S.H. 1971. Report of an UNDP/FAO mission for research and training in environmental control for growth of high value crops in Israel, New York, UN/FAO, Rome.
- Wittwer, S.H. 1981. Advances in protected environments for plant growth. Advances in food-producing systems for arid and semi-arid lands. Academic, New York.
- Wittwer, S.H. 1986. UNDP/FAO World Bank mission report-review of technical assistance requirements in the agricultural and food security sector in Egypt, Jan. 7 Jan.-6 Feb. Proc. Matl. Wkshp. on Protected Agr. Cairo, Egypt, 8-15 Dec.
- Wittwer, S.H., Y. Youtai, S. Han, and W. Lianzheng. 1987. The plastic revolution. Feeding a billion, frontiers in Chinese agriculture. Michigan State Univ. Press, East Lansing. p.381-390.
- Wittwer S.H. and R.E. Lucas. 1956. Celery production in Michigan. Michigan Agr. Ext. Bul. 339.
- Wittwer, S.H. and S. Honma. 1979. Greenhouse tomatoes, lettuce, and cucumbers. Michigan State Univ. Press, East Lansing.