significantly higher than the other 12 mulches tested. In 1995, no significant differences were recorded for relative strength.

Conclusions

The organic materials used in this study did not provide for beneficial crop responses compared to polyethylene mulching films. Our results confirm observations in other studies regarding the beneficial effect of polyethylene mulch compared to bare soil. Soil temperatures, total yields, fruit size, and soluble solids were improved significantly both years with most polyethylene mulching films. There were few significant differences in terms of crop performance between polyethylene mulches.

We found significant differences between mulches regarding durability, indicated by mulch ratings, removal time, and estimated cost of removal. Generally, there was a high degree of correlation between these different measurements with mulches that received higher ratings requiring less time and expense to remove. The significance of these differences between plastic films becomes apparent when one considers that there was a 250% and 362% increase between the lowest and highest estimated cost of removal for mulches in the 1994 and 1995 tests, respectively. The increased costs in 1994 and 1995 resulted in a difference of \$44 and \$63 per acre, respectively, between the lowest and highest estimated costs of removal. Therefore, the decision regarding which mulch to use should be based on durability and ease of removal, rather than on differences in how the various mulches affected crop growth.

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A Multilayer Soilless System for Greenhouse Tomato Production Pioneered in Shandong Province, People's Republic of China

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ADDITIONAL INDEX WORDS. *Lycopersicon esculentum*, multilayer cropping, photosynthesis, light interception

SUMMARY. A new multilayer soilless culture system for greenhouse tomato production is described. Experiments over two spring seasons and one winter season demonstrated faster plant growth rate, higher dry matter productivity, higher fruit yield, and better fruit quality with the multilayer soilless culture system compared to the traditional soil-based culture system. The multilayer soilless culture system is suggested as a replacement of the soil-based production system to achieve significant yield improvement in greenhouse tomato production.

At present, the key issues in greenhouse vegetable production are how to increase yields, decrease production costs, and maximize economic benefits. It is rec-

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ognized that the traditional soil culture methods will have limited future prospects in intensive agriculture. The advantages of soilless culture in greenhouse vegetable production have been confirmed by research findings and are proven by commercial experience (Agricultural University of Beijing, 1980; Bentley, 1955; Resh, 1978; Savage, 1985; Xing Yuxian, 1981). However, suitable models for cultivation and practical technology for low-input soilless production and management of greenhouse crops are still in the development stage. The purpose of this study was to provide some technological base for solving the above problem, through accelerated greenhouse vegetable production technology development, leading to significant increases in greenhouse crop production in China.

Materials and methods

Several experiments were carried out in a single-span heated glasshouse at Shandong Agricultural Univ., in Taian, Shandong Province, China, during 1982 and 1983, using a multilayer soilless culture system. The system was demonstrated during

1985–86; since then, it has been used widely for greenhouse tomato production in Shandong Province, and to some extent in other provinces in China.

Description of the multilayer soilless culture system

Triangular hydroponic culture (2.0 m in length, 0.2 m in width and height) channels were made of common iron sheets (Fig. 1). On either end of the channel, two small compartments (each 0.1 m long) were separated from the rest of the channel by vertical metal plates with slits to make them permeable to water. A nutrient solution supply tube was connected to one end of the channel, into the small compartment, while the other end was equipped with an adjustable siphon for variable drainage. The top 10 cm of the channel was filled with a growth medium (vermiculite or sand) held in place with a mesh screen. Below the growth medium, space was provided for a nutrient solution reserve. During most of the irrigation cycle, the channel was full, but, once the nutrient solution supply was interrupted, most of the solution drained

away through the siphon apparatus to either a lower channel or the main nutrient solution holding tank. The culture channels were hung parallel, 1.8 m apart, in three horizontal layers in north-south direction with 80 to 100 cm between the layers of channels.

Nutrient solution with a macro-nutrient concentration (ppm) of 140N- NO_3 -41P-234K-200Ca-43Mg-13S, an electrical conductivity (EC) of 2.0 to 2.5 $\text{mS}\cdot\text{cm}^{-1}$, and a pH of 5.5 to 6.5 was delivered 2 to 4 times daily, for 3 to 5 min each time, by an electric pump controlled by a timer. A typical irrigation cycle involved the operation of the pump until the top-layer channels were filled with nutrient solution and the siphons at one end of the channels were active for a predetermined time. Once the middle-layer

Fig. 1. (below) Diagrammatic illustration of the multilayer soilless culture system. (to the right, top) Photograph of an experimental prototype of the multilayer soilless culture system. (to the right, bottom) Commercial installation of the multilayer soilless culture system.

channels were filled with nutrient solution, their siphons were activated and most of their solution was transferred by gravity to the lowest layer of channels. The irrigation cycle was com-

pleted when the filling of the low layer channels with nutrient solution activated their siphons, transferring most of their nutrient solution back to the main holding tank.

'Lihong 2' tomato was used in all experiments. Transplants were raised in soil or soilless media (Ge Xiaoquang, 1982) and, when 30 days old, were planted at standard spacing in greenhouse groundbeds (about 2.5 plants/m²) or in the soilless media-filled channels (plants spaced at 0.2 m apart in channels, about 8 plants/m² of floor space). The winter-spring crops were planted during the first 10 days of January, while the fall-winter crops were planted in the middle of August. Plants were pruned to a single stem and trained according to standard greenhouse production practices (Papadopoulos, 1991).

Results and discussion

Performance of the multilayer soilless culture system

EFFECTS ON CHANNEL TEMPERATURE. The channel solution temperature over the long term varied in accordance with the air temperature. In the short term, however, when the air temperature

in the greenhouse dropped to about

10 °C during the winter-spring seasons, the channel temperature was still at 15 to 18°C. At midday, when the air temperature was >30 °C, the channel temperature was at 25 to 28 °C. In addition, the channel temperature was affected by the growth medium used. When sand was used, which is a good heat conductor, the channel temperature followed more closely the air temperature than when vermiculite (poor heat conductor) was used (e.g., 19 and 18 °C daily temperature average for sand and vermiculite, respectively, when the air temperature averaged 23 °C.)

EFFECTS ON THE OXYGEN CONTENT OF THE NUTRIENT SOLUTION. During the first 10 days of April, when the temperature of the nutrient solution was 20 to 21 °C, the oxygen content of the nutrient solution in the main holding tank was 5.54 mg·L⁻¹. The oxygen content in nutrient solution varied significantly among the three layers of channels. The tendency was for a progressive increase of the oxygen content from the top to the bottom layer of channels. A higher oxygen content in the nutrient solution being returned to the main holding tank (6.32 mg·L⁻¹) compared to the oxygen content of the nutrient solution in the holding tank (5.54 mg·L⁻¹) proved that the hydroponic system was effective at increasing the oxygen content of the nutrient solution when the solution was in circulation.

EFFECTS ON THE PH AND EC OF THE NUTRIENT SOLUTION. The nutrient solution main holding tank was sized adequately to allow the circulation of nutrient solution to the crop for 3 days, at 10 irrigation cycles daily, without excessive depletion or accumulation of ions. Typical profiles of pH and EC variation in the nutrient solution (Fig. 2) indicated a gradual increase in both pH and EC with the

Fig. 2. Typical profiles of nutrient solution pH and electrical conductivity (EC) variation over a 2- to 3-day period, in between nutrient solution changes, from the multilayer soilless culture system

aging of the solution. However, pH and EC remained within acceptable ranges and the frequency of nutrient solution renewal (i.e., every 3 days) was considered adequate.

Crop performance

PLANT GROWTH. Plants in soilless media grew and developed faster than plants in soil. Transplants raised in soilless media (i.e., sand or vermiculite) were ready for planting 10 days earlier, and fruit setting on their flower clusters took place 5 days earlier than in soil. Cropping in soilless media also resulted in further accelerated plant growth and development after transplanting (Table 1). Fresh mass of stems

and leaves of plants grown in soilless media was 47% to 84% higher than those of plants grown in soil. Furthermore, the fresh mass of roots of plants grown in soilless media in June 1983 was four times as great as that of soil grown controls. Strong root system development must have played an important role in ensuring strong and healthy shoots and a superior yield. Continued growth of assimilating organs was evident, even under shade conditions, i.e., at the bottom layer of plants growing in the soilless media (Table 1).

Effects on light interception and use

High population density and efficient canopy architecture maximizes light interception while minimizing self-shading. Judging on theoretical principles, increases in productivity would be expected to be closely related to increases in leaf area index (LAI) according to Beer-Lambert's law (Jiang Xianming, 1983; Sontakingan, 1982). In reality, however, increases in LAI above a certain point lead to inefficient light use (Charles-Edwards, 1982). The light intensity observations and related (derived) data from the application of Beer-Lambert's law are summarized in Table 2. These data indicate that the cumulative LAI of all three layers of the multilayer soilless culture system was 8.40, i.e., four times that of the soil control. Also, the extinction coefficient of corresponding canopy layers was significantly lower in the multilayer soilless culture system than in the soil control. These results indicate a more uniform distribution of the leaf area and, consequently, a higher efficiency in light energy interception in the multilayer culture system than in the soil control. The more complete overall light energy interception by

Table 1. Tomato plant growth in the multilayer soilless culture system

Treatment	Fresh mass of stems		Fresh mass of leaves		Fresh mass of roots		C/F ^y
	g ^x	% ^z	g ^x	% ^z	g ^x	% ^z	
Soilless culture							
Top layer	230.5	214.5	498.4	181.9	191.5	612.8	0.85
Middle layer	207.6	193.2	453.8	165.7	125.0	400.0	0.73
Bottom layer	156.1	145.3	255.2	93.2	65.0	208.0	0.86
Average	198.1	184.3	402.4	146.9	127.2	406.9	0.81
Soil culture	107.4	100.0	273.9	100.0	31.3	100.0	0.51

^xFresh mass expressed as a percentage of the total fresh mass of plants grown in soil.

^yC/F = weight ratio of nonphotosynthetic systems to photosynthetic systems.

^zMeans are averages of 3 to 15 plants, as determined in June 1983.

Table 2. Leaf area development and light interception by the multilayer canopy of the soilless culture system and by the conventional canopy of the soil-based system (December 1983, at Taian).

Treatment	Canopy segment ^z (cm)	LAI ^y	Cumulative LAI	Percent of incident light intensity (I _f /I ₀) ^x	Log of incident light (ln I _f /I ₀)	Extinction coefficient (K) ^w
Multilayer soilless culture	0-40	1.29	8.40	10.5	2.25	0.26
	41-80	0.95	7.11	18.6	1.68	0.24
	81-120	0.93	6.16	19.0	1.66	0.27
	121-160	0.94	5.23	20.0	1.61	0.30
	161-200	1.71	4.29	30.5	1.18	0.27
	201-240	1.99	2.58	59.9	0.51	0.20
	241-280	0.59	0.59	100.0	0	0
Soil culture	0-40	1.20	1.30	24.7	1.39	0.65
	41-80	0.77	0.84	52.5	0.64	0.76
	81-120	0.07	0.07	100.0	0	0

^zMeasured from the soil surface.

^yLAI = leaf area index.

^xI₀ = Light intensity above the canopy, I_f = light intensity below a particular leaf layer (F).

^wK = $[-\ln (I_f/I_0)] \div F$ (Beer-Lambert's law).

Fig. 3. Tomato leaf area and dry matter distribution by plant part in the multilayer soilless culture system (top) and the soil-based culture system (bottom), on a land area basis, and their effect on light attenuation by the two canopies.

Fig. 4. Typical profiles of daily illuminance variation and of corresponding variations in the net photosynthetic rates of tomato leaflets from crops in the multilayer soilless culture system, and soil-based culture system.

the multilayer culture system canopy, compared to the soil control canopy, is further evidenced by the variance in incident light reaching the soil surface (10.5% and 24.7% of incident light for the multilayer culture system and soil control, respectively; Table 2). Figure 3 further shows a significant contrast between the canopies of the multilayer soilless culture system, made up of several sparse leaf layers, and the uneven (in some cases too sparse, in other cases too crowded) leaf canopies

of the soil control. This contrast between the uniform light distribution achieved in the multilayer culture system and the acute shade conditions prevailing in the understory of the soil-based canopies lead to accelerated yellowing and wilting of leaves in the soil-based canopies. The more uniform distribution and interception of light in the multilayer culture system was probably responsible for the increased dry matter production with the multilayer culture system (Fig. 3). Some of the explanation for the higher dry matter production in the multilayer culture system is certainly the high photosynthetic ability in that system under high light intensity conditions (Fig. 4); the steep decline in the photosynthetic rate in the soil controls might be the result of water stress on heat-stressed plants due to localized

high rates of light interception. The overall higher photosynthetic productivity of the plants in the multilayer soilless culture system, and especially the high photosynthesis rates during the bright hours of the day, might indicate that these plants were more effectively supplied with water and nutrients than the plants grown in soil.

Effects on yield

Cropping in the multilayer system resulted not only in accelerated plant growth and development but also in an extended fruiting period and higher yield. Yield per unit area in the multilayer soilless system was 190% or 282% higher than that of the soil controls for the 1982 and 1983 winter-spring crops, respectively (Table 3). The corresponding yield increase in the fall-winter crop was 96%. The lower yield increase in the fall-winter crop compared to those of the winter-spring crops have probably been caused by the short and dull days of the late winter-early spring months. It appears that the advantage of the multilayer soilless system lies partly in its ability to intercept and use light more efficiently than the traditional soil-based system, particularly when light is in short supply.

Within reasonable limits, yield per unit area is proportional to population density, but yield per plant is inversely proportional to population density (Papadopoulos and Ormrod, 1990). However in this research, the yield per plant grown in soilless media was 55% to 87% higher than that of the soil-grown controls despite the significantly higher number of plants per unit area in the soilless system than in soil (about 3 times more) (Table 3). This is clearly an indication that the soilless system provided exceptionally good growing conditions despite the shading caused by the multilayered structure of the canopy. Individual plants maintained high levels of productivity leading to significant, area based, yield increases compared to soil. The high yield output of the multilayer soilless system was confirmed further in four large demonstration experiments during winter-spring and fall-winter 1985 and 1986 (212, 180, 642, and 222 m² plot size, respectively), where yield in the multilayer soilless system was always >9 kg·m⁻² compared to typical yields averaging 3 kg·m⁻² in soil-based systems.

Table 3. Tomato fruit yields produced with the multilayer soilless culture and the soil-based systems.

Year	Season	Treatment	Harvest time (d/m)	Yield ^z			
				kg/plant	% ^y	kg·m ⁻²	% ^y
1982	Winter-spring	Three-layer soilless culture	28/4-3/6	1.54	179	10.37	290
		Soil culture	19/5-28/6	0.86	100	3.57	100
	Fall-winter	Three-layer soilless culture	15/11-19/1	1.74	155	9.74	196
		Two-layer soilless culture	15/11-19/1	1.75	156	7.63	154
		Soil culture	19/11-11/1	1.16	100	4.96	100
1983	Winter-spring	Three-layer soilless culture	13/4-1/7	2.41	187	12.61	382
		Soil culture	3/5-28/6	1.29	100	3.30	100

^zHarvest plot size varied from 24-32 m² and 4.5-7.8 m² for the three-layer soilless culture and soil culture system, respectively.

^yTomato fruit yields produced with the multilayer soilless culture systems, as a percentage of corresponding yields with the soil-based systems.

EARLINESS OF YIELD. Harvesting of the winter-spring crops in the multilayer soilless system was 22 and 21 days earlier than that of controls in 1982 and 1983, respectively (Table 4). However, harvesting of the fall-winter crop in the multilayer soilless system was only 4 days earlier than that of the control. The advancement of the harvest onset of the winter-spring crops in the multilayer soilless system was equivalent (in number of days) to half of the whole harvest duration of the corresponding soil controls, and this played a major role in the sizable yield increases observed with the multilayer soilless system. The early yield increase with the use of the multilayer soilless method, compared to soil, was 95% to 118% for the winter-spring crops and 29% for the fall-winter crop (Table 4). Yield earliness is of particular importance during the winter-spring season because of the high demand for fresh salad vegetables and therefore the high value of the product.

YIELD DISTRIBUTION. Yield of tomato varied widely among different layers in the soilless culture system, apparently because of different light conditions; the tendency was top > middle > bottom layers. The rate of progressive yield decreases among layers in the winter-spring season exceeded 20% in 1982 (data not shown).

However, in 1983, it was kept below 20% because the plant support system was adjusted to improve light conditions in the middle and bottom layers (Fig. 5). Correspondingly, the yields of the middle and bottom layers were improved in 1983 compared to 1982, and this resulted in higher overall yields in 1983 (Table 3). Fruit production by individual plants in different layers was as follows: fruit of the first and second cluster made up about 60% of the total yield of the plants (Fig. 5). Furthermore, this fruit was of large, uniform size. The rest of the yield was provided by the remaining clusters (clusters 3, 4, and 5). The lower the layer, the more evident was the tendency for the most and best fruit to be on the first two clusters. Although the fruit from the first and second clusters in the bottom layer made up a high percentage of the yield in a single plant, at the same time these clusters had a very short time with peak yield, this being one of the factors affecting the overall yield productivity of individual plants.

FRUIT QUALITY. The fruit produced in the multilayer soilless system was more uniform and larger than that of the soil control (Table 5). The average fruit weight in the multilayer soilless system was 48% to 69% higher than that of the soil control. The content of soluble solids in fruit from the

top and middle layers was higher than that from the bottom layers, which was slightly lower than that of the controls. The flavor of fruit from the top and middle layers was better than the fruit from the bottom layer, which was similar to that of the soil control.

A serious concern could arise from the prospect of heavy metal ion release when nutrient solution corrodes the metal channels over time. Such ions could turn out at concentrations toxic to the plants and, even worse, to consumers. However, the eventual replacement of all metal components by plastic elements, as plastic becomes more and more available in many countries, would dispel any such concerns.

Conclusions

Results have been presented showing higher light interception, more efficient light use by photosynthesis, more dry matter production, and more tomato fruit yield with the multilayered soilless method compared to the soil control. This difference in performance is not necessarily an indication of a higher, or lower, productive capacity of a tomato crop grown in soilless media than in soil. However, the higher productivity of the plant canopies grown with the multilayered soilless system described in this paper, compared to the canopies grown in

Table 4. Chronological development of fruit yield in the multilayer soilless and the soil-based culture systems.

Year	Cropping season	Treatment	Harvesting				Early yield ^z (kg·m ⁻²)
			Start (d/m)	End (d/m)	Duration (days)	Earliness (days)	
1982	Winter-spring	Soilless-multilayer	28/4	3/6	37	22	2.91
		Soil culture	19/5	28/6	41	---	1.49
	Fall-winter	Soilless-multilayer	15/11	19/1	66	4	1.93
		Soil culture	19/11	11/1	54	---	1.49
1983	Winter-spring	Soilless-multilayer	13/4	1/7	79	21	2.66
		Soil culture	3/5	28/6	56	---	1.22

^zYield harvested during first 10 days.

soil, points to the limitations of the traditional soil-based production system, as practiced in many countries. These limitations to productivity in the soil-based system appear to include a lack of opportunity for sufficient canopy development, short-lived leaves due to leaf crowding and shad-

ing, and, possibly insufficient capacity to supply water and nutrients. The yield results from our studies have provided clear evidence of the potential for large yield increases when the traditional soil-based system is replaced with a multilayer soilless system, as described herein.

Fig. 5. Chronological development of tomato fruit yield in the multilayer soilless culture system over an entire cropping season, by layer of channels and by cluster.

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Table 5. Fruit quality indices of tomato fruit produced in soil or with the multilayer soilless culture system.

Treatment	Fruit number examined	Fruit mass		Soluble solids (% of FW) ^y	Taste
		(g/fruit)	% ^z		
Soilless culture					
Top layer	1055	175	168.6	5.50	Strongly sweet and acid
Middle layer	882	174	168.1	4.80	Acid and sweet
Bottom layer	880	153	148.3	4.67	Weakly acidic and sweet
Soil culture	248	103	100.0	4.76	Weakly acidic and sweet

^zFruit mass expressed as a percentage of the mass of fruit produced in soil.

^yMeans are averages of six fruit samples.