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# Spectral Quality Affects Disease Development of Three Pathogens on Hydroponically Grown Plants

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***Abstract.*** **Plants were grown under light-emitting diode (LED) arrays with various spectra to determine the effects of light quality on the development of diseases caused by tomato mosaic virus (ToMV) on pepper (*Capsicum annuum* L.), powdery mildew [*Sphaerotheca fuliginea* (Schlectend:Fr.) Pollaci] on cucumber (*Cucumis sativus* L.), and bacterial wilt (*Pseudomonas solanacearum* Smith) on tomato (*Lycopersicon esculentum* Mill.). One LED (660) array supplied 99% red light at 660 nm (25 nm bandwidth at half-peak height) and 1% far-red light between 700 to 800 nm. A second LED (660/735) array supplied 83% red light at 660 nm and 17% far-red light at 735 nm (25 nm bandwidth at half-peak height). A third LED (660/BF) array supplied 98% red light at 660 nm, 1% blue light (BF) between 350 to 550 nm, and 1% far-red light between 700 to 800 nm. Control plants were grown under broad-spectrum metal halide (MH) lamps. Plants were grown at a mean photon flux (300 to 800 nm) of 330 $\mu mol \cdot m^{-2} \cdot s^{-1}$ under a 12-h day/night photoperiod. Spectral quality affected each pathosystem differently. In the ToMV/pepper pathosystem, disease symptoms developed slower and were less severe in plants grown under light sources that contained blue and UV-A wavelengths (MH and 660/BF treatments) compared to plants grown under light sources that lacked blue and UV-A wavelengths (660 and 660/735 LED arrays). In contrast, the number of colonies per leaf was highest and the mean colony diameters of *S. fuliginea* on cucumber plants were largest on leaves grown under the MH lamp (highest amount of blue and UV-A light) and least on leaves grown under the 660 LED array (no blue or UV-A light). The addition of far-red irradiation to the primary light source in the 660/735 LED array increased the colony counts per leaf in the *S. fuliginea*/cucumber pathosystem compared to the red-only (660) LED array. In the *P. solanacearum*/tomato pathosystem, disease symptoms were less severe in plants grown under the 660 LED array, but the effects of spectral quality on disease development when other wavelengths were included in the light source (MH-, 660/BF-, and 660/735-grown plants) were equivocal. These results demonstrate that spectral quality may be useful as a component of an integrated pest management program for future space-based controlled ecological life support systems.**

Several types of plant irradiation sources have been proposed for use in space-based controlled ecological life support systems (CELSS) (Barta et al., 1992; Sager and Wheeler, 1992). Light-emitting diodes (LEDs) have the advantages of low mass and volume, solid-state construction, long-life, and reduced heat output compared to high-intensity discharge lamps (Barta et al., 1992; Brown et al., 1995; Bula et al., 1991). Furthermore, solid-state diodes emitting light of specific and restricted wavelengths might be used in lighting arrays that would permit the independent selection of differing intensities of red, blue, and far-red wavelengths for optimum production of diverse plant species.

Plants in CELSS modules will be colonized by a diversity of microorganisms, some of which may cause plant health problems (Gonzales et al., 1996; Nelson, 1987; Schuerger and Mitchell, 1992). LED arrays of unique spectral output that might inhibit the development of specific plant diseases would be extremely useful in a CELSS integrated pest management (IPM) program. For example, spectral quality can have significant effects on plant physiology (Sage, 1992; Senger, 1982; Smith, 1982) that could alter plant resistance to microbial challenge. Furthermore, many fungal (Honda and Nemoto, 1985; Vakalounakis, 1992; Vakalounakis and Christias, 1981), bacterial (Guo et al., 1993; Smith and Kennedy, 1970), and viral (Coast and Chant, 1970; Thomas et al., 1988) diseases of plants are affected by the spectral quality of the primary light source. Foliar fungal diseases of various crops have been suppressed in greenhouses when UV-A (320 to 400 nm) absorbing vinyl films were used to cover the structures (Honda and Nemoto, 1985; Honda et al., 1977; Sasaki et al., 1985). The apparent mechanism in disease control was the suppression of spore germination and sporulation of the fungal pathogens caused by extremely low levels of blue or UV-A light (Honda et al., 1977; Vakalounakis and Christias, 1981).

The objective of our study was to test whether LEDs could be used to suppress plant diseases caused by three pathogens on separate host species by altering spectral quality of the primary light source. A preliminary report on a portion of this study was published previously (Schuerger and Brown, 1994).

## Materials and Methods

*Plant cultural conditions.* Portions of the procedures for seed germination and plant maintenance have been described (Brown et al., 1995; Schuerger et al., 1997). Seeds of pepper (*Capsicum annuum*, cv. Hungarian Wax), cucumber (*Cucumis sativus*, cv. Spacemaster), and tomato (*Lycopersicon esculentum*, cv. Microtom) were germinated in 2.5-cm cubes of rockwool (Grodania A/S, Hedehusene, Denmark) under a 250-W metal halide (MH) lamp. Light intensity was adjusted to a photosynthetic photon flux (PPF) of 250 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at 6 cm above the surface of the rockwool. Seedlings were watered daily with a complete nutrient solution (Schuerger and Mitchell, 1992) and maintained under the 250-W MH lamp for 21 d. Plants were transferred to 4-L polypropylene tanks filled with complete nutrient solution in which the hydrogen ion concentration was adjusted daily to pH 5.5 with $HNO_3$ at 0.02 $mol \cdot L^{-1}$ or KOH at 0.02 $mol \cdot L^{-1}$, and in which the nutrient solution was aerated continuously. The electrical conductivity of fresh nutrient solution was 1700 $\mu S \cdot cm^{-1}$. Twenty-one-day-old pepper or cucumber plants, or 17-day-old tomato plants, were transferred to LED arrays or to a second MH lamp (400-W), which served as a control treatment. Ambient temperature (24.5 ± 2.2 °C), root temperature (22.4 ± 1.0 °C), and relative humidity (RH) (58% ± 8%) for plants grown under each light source were measured with an electronic environmental monitoring system (Muller and Harriott, 1984).

Spectral characteristics of the LED and MH light sources have been described by Brown et al. (1995). In brief, LED arrays were composed of one or more of the following: red LEDs with peak emissions of 660 nm (25 nm bandwidth at half-peak height) (model 3009A001; Quantum Devices, Barnveld,

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Wis.), far-red LEDs with peak emissions at 735 nm (25 nm bandwidth at half-peak height) (model 3009A002; Quantum Devices), or blue fluorescent lamps (model BF6165-12; JKL Components Corp., Paccoima, Calif.). One LED (660) array supplied 99% red light at 660 nm and 1% far-red light between 700 to 800 nm. A second LED (660/735) array supplied 83% red light at 660 nm and 17% far-red light at 735 nm. A third LED (660/BF) array supplied 98% red light at 660 nm, 1% blue light (BF) between 350 to 550 nm, and 1% far-red light between 700 to 800 nm. Control plants were grown under broad-spectrum 400-W MH lamps. Plants were grown at a mean photon flux (300 to 800 nm) of 330 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (PPF = 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$) measured from the tops of the plant canopies under a 12-h day/night photoperiod. Opaque plastic barriers were erected among the light sources to prevent cross-contamination of light among treatments. To reduce thermal infrared irradiation, the MH lamp was housed in a stainless steel luminaire suspended over a 3-cm-deep, deionized water barrier supported by a 5-mm-thick tempered-glass plate. The water temperature in the barrier was maintained at 25 °C by recirculation through a Lauda RMS-20 water chiller (Brinkman Instruments, Westbury, N.Y.). When the water barrier was used under the MH lamp, leaf temperatures among all light treatments and plant species were ±0.5 °C of each other, and within ±1 °C of the ambient temperature.

*Plant inoculation procedures.* Peppers were inoculated with tomato mosaic virus (ToMV) (EPCOT isolate; Pategas et al., 1989) 12 d after plants were transferred from the seed germination tray to the LED or MH light sources. Three pepper plants in each of two separate 4-L tanks were transferred to each light source. To prevent cross-contamination by ToMV between noninoculated and inoculated peppers, plants in one tank were separated from plants in the second tank by suspending clear plastic sheets from the support structure of each light source. Plants in one tank for each light source served as noninoculated controls and plants in the second tank per light source were inoculated with ToMV. Inoculum of ToMV was prepared by triturating systemically infected 'Hungarian Wax' pepper leaves in phosphate buffer (pH 7) at 0.2 $mol \cdot L^{-1}$. Systemically infected peppers (6- to 10-week-old plants) used as inoculum sources were maintained in an isolated greenhouse at 24 to 30 °C and 60% to 85% RH throughout the experiment. For the LED experiments, two leaves per plant were dusted with very fine carborundum (320-grit) and inoculated with ToMV leaf extract by rubbing the inoculum onto leaves with autoclaved cheesecloth. Inoculated leaves were washed with a stream of sterile deionized water to remove excess inoculum. Plants were observed daily for the development of symptoms. Plants were maintained for 9 d after ToMV inoculation and then harvested to determine plant fresh masses and percentage of plants wilting at 9 d. The percentage of biomass reduction of the inoculated plants vs. the noninoculated plants was calculated. The ToMV/pepper experiment was conducted four times with a water barrier under the MH lamp and four times without the water barrier under the MH lamp.

Cucumber plants were grown under the various light sources for 10 d before leaves were inoculated with powdery mildew (*Sphaerotheca fuliginea*). Cultures of *S. fuliginea* were maintained on *C. sativus* cv. Corona in an isolated greenhouse maintained at 24 to 30 °C and 60% to 85% RH throughout the experiment. Inoculum of *S. fuliginea* was prepared by dispersing conidia in 50 mL of Fluorinet FC-43 (3-M Co., St. Paul, Minn.) to achieve a density of 2000 propagules/mL. Two leaves per each of three randomly selected plants were inoculated by aspirating 0.25 mL of the conidium suspension onto each leaf. Plants were maintained under each light source for 11 d after inoculation, and then the numbers and diameters of powdery mildew colonies were determined for one of the inoculated leaves per plant. Plants were inspected twice each day after leaf inoculation to assure that all inoculated leaves were fully exposed to the light emitted by the LED arrays or MH lamp. Inoculated leaves were gently repositioned in the cucumber canopies if any portion of the leaf surface was shaded by other parts of the plant canopy. The experiment was conducted three times with a water barrier under the MH lamp.

Tomato plants were grown under the various light sources for 14 d before inoculation. Three of the six plants were inoculated with *Pseudomonas solanacearum* (isolate H-3, obtained from D.O. Chellemi, Univ. of Florida, Institute of Food and Agricultural Sciences, Quincy). Cultures of *P. solanacearum* were grown for 48 h at 28 to 30 °C on nutrient agar (Dhingra and Sinclair, 1985). Tomato plants were inoculated at the first and second leaf axils of the main stem by injecting 100 µL of a $5.5 \times 10^8$ colony-forming units/mL bacterial suspension into each leaf axil. Noninoc-ulated plants were injected with 100 µL of sterile deionized water. Tomato plants were maintained for 14 d after inoculation. Noninoculated and inoculated tomato plants were measured for plant fresh mass, plant height, and plant wilt. In addition, main stems of both the noninoculated and inoculated plants were split longitudinally and the dimensions of internal necroticized tissues were measured. The experiment was conducted three times with a water barrier under the MH lamp.

*Statistical procedures.* Analyses of data were conducted with the Statistical Analysis System (SAS) (SAS Inst., Cary, N.C.). Data from each of the three pathogen–host experiments were subjected to an analysis of variance (PROC GLM) followed by least-squares mean separation tests ($P \leq 0.05$).

## Results

*Noninoculated plants.* Growth characteristics of noninoculated control plants already have been described more fully (Brown et al., 1995; Brown and Schuerger, 1993; Schuerger et al., 1997). Plant biomass in peppers was highest under MH light, intermediate under 660/BF light, and lowest under 660 or 660/735 light (Table 1). Plant biomass in cucumbers was highest under MH light, intermediate under 660/BF or 660/735 light, and lowest under 660 light (Table 2). Plant biomass and stem height in tomatoes were generally similar among light treatments (Table 3). A preliminary analysis of the data from the ToMV/pepper pathosystem indicated that the presence of the water barrier had no effect on the growth of noninoculated or inoculated plants, nor did the presence of the water barrier affect the development of disease symptoms (data not shown). Thus, the data from the ToMV/pepper study were combined and analyzed as one experiment.

*Inoculated plants.* Disease in the ToMV/pepper pathosystem was characterized by systemic mottling, leaf chlorosis, petiole and stem necrosis, and plant wilt. Disease symptoms were most severe on inoculated plants grown under the 660 or the 660/735 LED arrays (Table 1). Disease severity was lowest for inoculated plants grown under the MH lamp. However, leaf chlorosis and systemic mottling caused by ToMV were first observed between 4 and 5 d on all inoculated plants grown under the LED arrays or MH lamp. Fresh mass of inoculated plants grown under the 660/BF light source was significantly lower than for the MH-grown plants and significantly higher than for the 660- or the 660/735-grown plants. However, when disease severity was calculated as the percentage of reduction in plant fresh mass of inoculated compared to noninoculated plants, MH- and 660/BF-grown plants were similar. All pepper plants inoculated with ToMV and grown under the 660 or 660/735 LED arrays wilted between 6 and 7 d after plant inoculation (Table 1). In contrast, 9 d after plant inoculation, only 54% and 79% of plants grown under the MH lamp or 660/BF LED array, respectively, had wilted. Plant wilt in peppers grown under the 660 or the 660/735 LED arrays was associated with a severe and rapid collapse of the main stem between the second and the fourth internodes. Stem necrosis was absent in inoculated plants grown under the 660/BF or MH light sources, but plant wilt was associated with leaf or petiole necrosis.

Foliar colonies of *S. fuliginea* on cucumber under all light sources were first observed 7 d after inoculation. The distribution of powdery mildew colonies on inoculated leaves was generally random, and there was no indication that the distance from the light sources or plant canopy structure had any effect on colony count or diameter. The number of powdery mildew colonies per leaf was highest under MH, intermediate under 660/BF or 660/735 LEDs, and lowest under 660 LEDs (Table 2; Fig. 1). The diameter of powdery mildew colonies was largest on inoculated leaves grown under the MH lamp. In contrast, the diameters of powdery mildew colonies on inoculated leaves grown under the LED arrays were similar but significantly smaller than the diameters of colonies on cucumbers grown under the

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Table 1. Effects of spectral quality on the development of tomato mosaic virus (ToMV) in peppers.

| Growth characteristic | Spectral array[z] MH | 660/BF | 660 | 660/735 |
|---|---|---|---|---|
| Plant fresh mass (g) | | | | |
| Control[y] | 43.7 aA | 35.7 bA | 28.3 cA | 30.3 cA |
| Inoculated[y] | 15.7 aB | 11.5 bB | 7.2 cB | 7.3 cB |
| Inoculated as a percentage of control[x] | 37 a | 32 ab | 26 bc | 24 c |
| Plants wilted (%)[w] | 54 | 79 | 100 | 100 |

[z]MH = metal halide lamp; BF = blue fluorescent lamps; 660 = red LEDs; 735 = far-red LEDs.
[y]Mean separation among spectral arrays in rows (lowercase) and between control vs inoculated treatments in columns (uppercase) based on analysis of variance (ANOVA) and protected Fisher's least-squares significant difference (LSD) tests ($P \leq 0.05$; n = 24).
[x]Mean separation in the row based on ANOVA and Fisher's LSD tests ($P \leq 0.05$; n = 8); data were not transformed prior to analysis.
[w]The percentage of plants wilted at the end of the experiment (measured 9 d after plants were inoculated with ToMV and incubated under the MH or 660/BF lamps, or 7 d after plants were inoculated with ToMV and incubated under the 660 or 660/735 LED arrays).

Table 2. Effects of spectral quality on the development of *Sphaerotheca fuliginea* on cucumbers.

| Growth characteristics | Spectral array[z] MH | 660/BF | 660 | 660/735 |
|---|---|---|---|---|
| Fresh mass (g), noninoculated control plants | 90 a[y] | 41 bc | 34 c | 65 b |
| Colonies/leaf | 121 a | 56 b | 20 c | 43 b |
| Colony diameter (mm) | 5.4 a | 3.9 b | 3.4 b | 3.5 b |

[z]MH = metal halide lamp; BF = blue fluorescent lamps; 660 = red LEDs; 735 = far-red LEDs.
[y]Mean separation within rows based on analysis of variance and protected Fisher's least-squares mean separation tests ($P \leq 0.05$; n = 9).

Table 3. Effects of spectral quality on the development of *Pseudomonas solanacearum* on tomatoes.

| Growth characteristic | Spectral array[z] MH CON[y] | MH INOC | 660/BF CON | 660/BF INOC | 660 CON | 660 INOC | 660/735 CON | 660/735 INOC |
|---|---|---|---|---|---|---|---|---|
| Plants | | | | | | | | |
| Fresh mass (g) | 32.0 a[x] | 19.2 d | 28.1 ab | 19.7 d | 24.6 bc | 23.4 c | 28.2 a | 22.4 cd |
| Height (cm) | 14.2 b | 12.1 b | 19.2 a | 16.1 b | 20.1 a | 18.8 a | 18.7 a | 18.2 a |
| Wilted (%)[w] | --- | 78 | --- | 22 | --- | 0 | --- | 33 |
| Lesion length (cm)[v] | --- | 3.1 a | --- | 3.5 a | --- | 3.1 a | --- | 3.5 a |

[z]MH = metal halide lamp; BF = blue fluorescent lamps; 660 = red LEDs; 735 = far-red LEDs.
[y]CON = noninoculated control plants; INOC = inoculated plants.
[x]Mean separation within rows based on analysis of variance and protected Fisher's least-squares significant difference tests. ($P \leq 0.05$; n = 9).
[w]The total percentage of plants wilted at the end of the experiment (measured 14 d after plants were inoculated with *P. solanacearum*).
[v]Lesion length was measured as the longitudinal dimension of internal stem necrosis caused by *P. solanacearum* measured 14 d after plant inoculation.

MH lamp (Table 2). Although the colony diameters were similar among LED-grown plants, the visual appearance of the powdery mildew colonies differed dramatically (Fig. 1). Colonies on leaves grown under the 660 LED array contained very sparse mycelium and induced very little leaf necrosis. In contrast, colonies on MH-, 660/BF-, and 660/735-grown leaves had more robust mycelium and induced necrotic lesions on the leaves. Furthermore, microscopic observations of the powdery mildew colonies on LED-grown plants indicated that conidiation was dramatically inhibited on leaves grown under the 660 LED array and slightly suppressed on leaves grown under the 660/BF or 660/735 LED arrays as compared to MH-grown plants (data not shown).

The effects of spectral quality on the development of *P. solanacearum* in tomatoes (Table 3) were somewhat more equivocal than in the ToMV/pepper or *S. fuliginea*/cucumber pathosystems. First, plant fresh masses between inoculated and noninoculated tomatoes differed significantly with MH-, 660/BF-, and 660/735-grown plants, but not with 660-grown plants. Second, plant height between inoculated and noninoculated tomatoes differed significantly with 660/BF-grown plants, but not in the other treatments. Third, the percentage of plants wilting at the end of each trial was highest for the MH-grown plants, intermediate for the 660/BF- or 660/735-grown plants, and zero for the 660-grown plants. Fourth, the size, shape, and coloration of internal necrotic stem lesions were similar in tomatoes grown under all light sources (Table 3; Fig. 2). Internal stem lesions were very consistent among inoculated plants within a given repetition of an experiment and consistent among repetitions of the experiment, even though plant symptoms (as measured by fresh mass and shoot height) and plant wilt differed greatly among treatments and among experiments. Overall, disease symptoms caused by *P. solanacearum* in tomato were lowest in the 660-grown plants and variable in plants grown under the other light sources.

## Discussion

Spectral quality can have a profound effect on plant growth and physiology (Sage, 1992; Senger, 1982; Smith, 1982) and inhibits disease development in several host–pathogen systems (Coast and Chant, 1970; Honda and Nemoto, 1985; Smith and Kennedy, 1970; Thomas et al., 1988; Vakalounakis and Christias, 1981). The three pathosystems we tested were selected to determine if the effects of red light (either alone, or supplemented with blue or far-red irradiation) on disease development were similar among the specific pathogens. Our results indicate that spectral quality affected each pathosystem differently. In the ToMV/pepper pathosystem, plant disease symptoms were least in plants grown under light sources that contained blue and UV-A irradiation (MH lamp and 660/BF LED array) and worst in plants grown under light sources that lacked blue and UV-A irradiation (660 and 660/735 LED arrays). In contrast, disease development in the *S. fuliginea*/cucumber pathosystem was worst on leaves grown under the MH lamp (highest amount of blue and UV-A irradiation) and least on leaves grown under the 660 LED array (no blue or UV-A irradiation). In the *P. solanacearum*/tomato pathosystem, disease was apparently mildest in plants grown under the 660 LED array, but the effects of spectral quality on disease development when other wavelengths of light were included in the light source (MH-, 660/BF-, or 660/735-grown plants) were equivocal.

The mechanisms involved with the effects of spectral quality on disease development in the ToMV/pepper, *S. fuliginea*/cucumber, and *P. solanacearum*/tomato pathosystems are not known. However, the results of our study support the conclusion that blue and UV-A irradiation (and possibly far-red irradiation) can modify disease development when plants are grown under LEDs. For example, blue light appears to be required by 'Hungarian Wax' peppers to maintain normal attributes of host resistance. Brown et al. (1995) and Brown and Schuerger (unpublished) found that identical light treatments as were used in the current study produced significant reductions in plant dry mass, number of leaves per plant, leaf chlorophyll concentration, photosynthetic rate, and stomatal conductance of 'Hungarian Wax' peppers when blue light was omitted from the light source. Furthermore, Schuerger et al. (1997) observed that reductions in blue light decreased the thickness of secondary xylem tissues, number of vessels per $mm^2$, and cross-sectional area of vessels in first and third internodes of such peppers. We conclude that a lack of blue light inhibited normal plant growth and development in 'Hungarian Wax' peppers that then resulted in a reduction of host resistance to ToMV. The stem collapse between 6 and 7 d after ToMV inoculation of peppers grown under the 660 or 660/735 LED arrays was attributed to reductions in the secondary xylem in the main stems of peppers (Schuerger et al., 1997), which likely lowered their physical integrity. However, the effects

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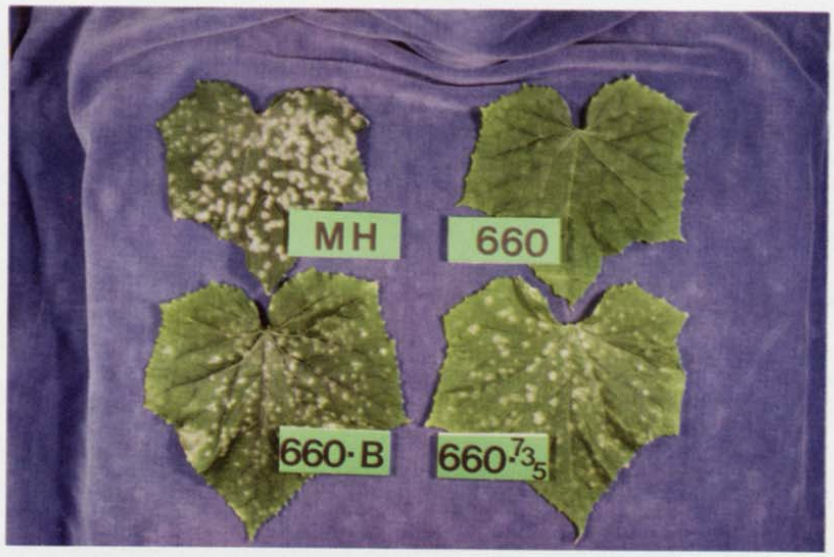


Fig. 1. Cucumber leaves ('Spacemaster') inoculated with *Sphaerotheca fuliginea* grown under a metal halide (MH) lamp, or under red (660), red + blue (660-B), or red + far-red (660-735) light-emitting diode (LED) arrays. Number and diameters of colonies of *S. fuliginea* were highest on cucumber leaves grown under the MH lamp and lowest on cucumber leaves grown under the 660 LED array.

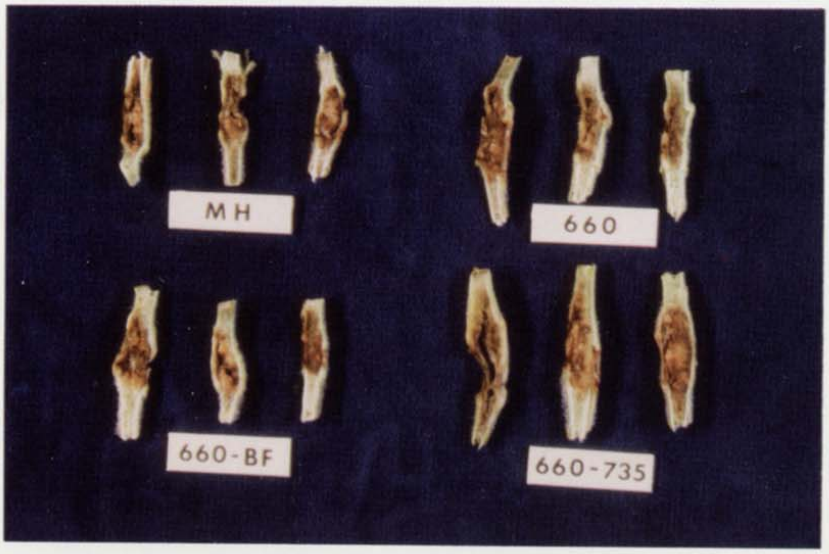


Fig. 2. Longitudinal stem-sections of tomatoes ('Microtom') inoculated with *Pseudomonas solanacearum* and grown under a metal halide (MH) lamp, or under red (660), red + blue (660-BF), or red + far-red (660-735) light-emitting diode (LED) arrays. Necrotic stem-lesions caused by *P. solanacearum* were similar in size and severity in inoculated plants grown under the MH lamp or LED arrays. Necrotic stem-lesions were absent in control plants inoculated with sterile deionized water.

of blue light on initial ingress of ToMV virions into pepper leaves, viral replication within individual cells, short-distance movement of virions within a leaf, or systemic movement of virions in a plant should not be ignored. Blue and ultraviolet light increase systemic transport of tomato yellow top virus on tomato [*L. peruvianum* (L.) Mill.] (Thomas et al., 1988), increase numbers of local lesions with tobacco mosaic virus in beans (*Phaseolus vulgaris* L.) (Semal, 1964), and alter the susceptibility of irradiated leaves of beans to tobacco necrosis virus (Benda, 1955).

Results of the *S. fuliginea*/cucumber study may be explained on the basis of the effects that blue and far-red irradiation have on disease development, spore germination, and sporulation reported for other foliar fungal pathogens (Leach, 1962; Senger, 1982; Vakalounakis, 1992). Blue light present in the MH lamp and 660/BF LED array may have stimulated conidium germination and growth of mycelium on inoculated cucumber leaves, as compared to plants grown under the red-only (660 nm) LED array. Attenuation of blue and ultraviolet irradiation by vinyl coverings of greenhouses reduces the incidence of several foliar fungal diseases of a variety of plants (Honda et al., 1977; Honda and Nemoto, 1985; Sasaki et al., 1985; Vakalounakis and Christias, 1981). Addition of far-red irradiation (735 nm) also increased disease development in the *S. fuliginea*/cucumber pathosystem, as compared to the red-only (660 nm) LED array. Vakalounakis (1992) showed that infrared-absorbing plastic films (attenuation >700 nm) reduced diseases of tomatoes caused by several fungi.

The effects of spectral quality on the development of *P. solanacearum* in tomatoes are more difficult to interpret than the results of the ToMV/pepper and *S. fuliginea*/cucumber studies. Most characteristics used to measure the effects of spectral quality on disease development indicated that tomato plants grown under red light (660 nm) were the most resistant to *P. solanacearum*, even though the size and shape of the internal necrotic stem lesions were similar among plants grown under all four light sources. However, results from our study and from the literature (Guo et al., 1993; Smith and Kennedy, 1970) do support the conclusion that bacterial diseases of plants can be affected by shifts in spectral quality.

Microorganisms that are airborne or occur as surface contaminants on crew and equipment in space-based CELSS modules will comprise the majority of microbial species associated with plants. It is likely that a comprehensive IPM program will exclude many traditional plant pathogens (e.g., soilborne fungal pathogens and nematode parasites) from space-based CELSS. However, it also is likely that microorganisms will constitute a threat to plant health in CELSS crop production systems. LED technologies may have an advantage over broad-spectrum light sources, in that LEDs may permit the selection of spectral ranges ideal for optimum plant growth and development in a CELSS while concomitantly providing a useful IPM tool in the management of certain plant diseases. However, the overall effects of LED lighting on CELSS stability and productivity will have to be considered. For example, in our study, peppers grown under MH light as compared to LED light had the largest plant biomass and lowest disease caused by ToMV. In contrast, plant growth was retarded under light conditions (660 LED array) that suppressed disease development in the *S. fuliginea*/cucumber and *P. solanacearum*/tomato pathosystems. Control options in any IPM program can interfere with crop production, but trade-offs between crop losses due to disease and the efficiency, cost, and practicality of the IPM practices should be considered.

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