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SPECTRAL FILTERING FOR PLANT PRODUCTION

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RADIATION AND PLANTS

In the scheme of living things, plants play the vital role of *producers* in the food chain that is crucial to all life. Animals and microbes, on the other hand, are generally *consumers* and/or *decomposers* of the foodstuffs produced by plants. Animals and humans utilize light from a portion of the electromagnetic spectrum radiated by the sun for 'vision' to enable transfer of information that relates shape and color of objects and perceives position and motion. For plants, however, light is not only a medium for information transfer; it is also a medium for energy transfer that enables the crucial processes of **photosynthesis** and **photomorphogenesis**. From light, plants may not be able to 'see' objects and to guide motion, yet they can perceive intensity, direction and spectral composition of radiation, can keep track of time and can adjust their biological processes to optimize their capacity for survival within the environment in which they are placed. Consequently, it can be surmised that plants have their own form of 'vision' related to the medium of light.

Both plants and animals have one general commonality in their perception of light. They both are sensitive primarily to the 400 to 700 nm wavelength portion of the electromagnetic spectrum. This is referred to as the visible spectrum for animals and as the photosynthetically active radiation (PAR) spectrum for plants. Within this portion of the spectrum, animals perceive colors. Relatively recently it has been learned that within this same spectral range plants also demonstrate varying responses at different wavelengths, somewhat analogous to the definition of various colors at specific wavelengths. Although invisible to the human eye, portions of the electromagnetic spectrum on either side of the visible range are relatively inactive photosynthetically but have been found to influence important biological functions. These portions include the ultraviolet (UV≈280-400 nm) and the far-red (FR≈700-800 nm).

The basic photoreceptor of plants for photosynthesis is chlorophyll. It serves to capture radiant energy which combined with carbon dioxide and water produces oxygen and assimulated carbon, used for the synthesis of cell wall polysaccharides, proteins, membrane lipids and other cellular constituents. The energy and carbon building blocks of photosynthesis sustain growth of plants. On the other hand, however, there are other photoreceptors, or pigments, that function as signal transducers to provide information that controls many physiological and morphological responses of *how* a plant grows. Known photomorphogenic receptors include **phytochrome** (the red/far-red sensor in the narrow bands of 655-665 nm and 725-735 nm ranges, respectively) and **"cryptochrome"** (the hypothetical UV-B sensor in the 280-320 nm range). Since the USDA team of W. L. Butler, S. B. Hendricks, H. A. Borthwick, H. A. Siegleman and K. Norris in Beltsville, MD detected by spectroscopy, extracted and identified phytochrome as a protein in

the 1950's, many other investigators have found evidence of its control functions in plants. Considerably less, however, is known about the yet non-isolated cryptochrome.

The information-transferring roles of photoreceptors in plants at specific spectral ranges quite naturally stimulated plant scientists and engineers to consider physically manipulating light to achieve desired physiological and morphological characteristics. One way to manipulate light is to filter it through materials that selectively transmit portions of the sun's spectrum in and near the PAR range.

NATURALLY FILTERED RADIATION

Radiation from the sun is naturally filtered in numerous ways before it reaches plants at the earth's surface. Approximately 30% of the sun's radiation actually never penetrates the earth's atmosphere but is reflected back into space by clouds and other particles. This is primarily the ultraviolet part of the spectrum. About 20% evaporates water to form clouds. Slightly less than 50% is converted into heat and reradiated into outer space as infrared radiation. Only about 0.02% of the sun's energy is actually utilized by plants.

Another interesting fact is that numerous determinations of daylight spectral distributions have consistently indicated that the red to far-red ratio (R/FR ratio) is remarkably constant. Whenever the solar angle is greater than 10°, the R/FR ratio averages 1.15 ± 0.02. Although clouds and weather conditions reduce the intensity (quantity) of radiation as much as tenfold, they virtually have no effect on R/FR. This remarkable constancy of R/FR in daylight affords a standard value against which natural radiation, modified by spectral filtering techniques, can be compared. Virtually no natural terrestrial situations permit the R/FR ratio to go higher than the 1.15 daylight value.

Diurnal fluctuations predictably occur in daylight spectral distributions across the 400-800 nm range at fixed, short time intervals during the day (Hughes et al, 1984). Two primary fluctuations were observed as the solar angle diminishes toward dawn and dusk when the proportion of direct versus diffuse radiation declines, Figure 1. First, and more markedly, there is a pronounced relative peak in the blue (B≈400-500nm) region. Secondly, since direct beams traverse a longer path through the atmosphere at this

Figure 1. Light quality surface for unshaded daylight at Sutton Bonington, UK on 7 July 1981 (Hughes et al, 1984).

time of day, atmospheric absorption and scattering is increased. Thus shorter wavelengths are depleted and a small, yet measurable, drop occurs in the R:FR ratio. This striking rise in the B
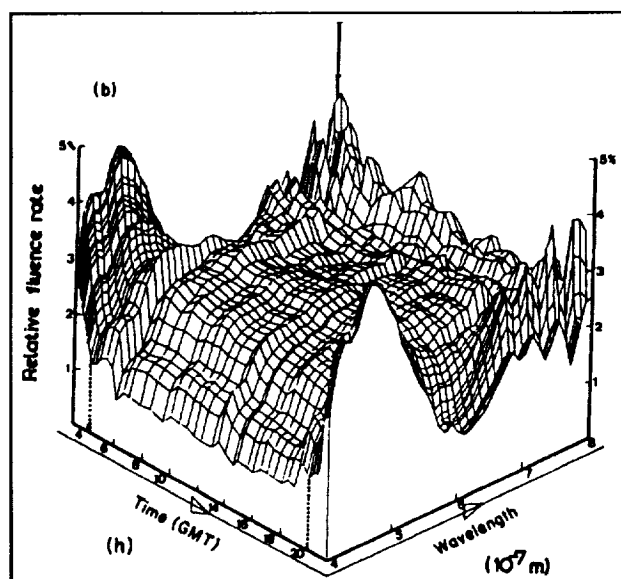
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level at dusk could suggest that a photoreceptor in this range acts to detect the end of daylight.

In the canopies of plants, vegetation absorbs R and is relatively transparent to FR. Densities and orientations of crop canopies, presence of competing plants and residues on the ground and heliotrophic movement of leaves can all contribute to far-red reflection patterns which may induce crop plants with fewer branches and longer internodes (Kasperbauer, 1987). Consequently, there can be major reductions in the R/FR ratio within plant canopies. Total irradiance may be reduced by a factor of 100 below the canopy compared to direct sunlight throughout the spectrum with the exception of the far-red (Smith, 1986). Therefore, canopy shade is a natural filter that can greatly alter the R/FR spectral composition and, subsequently, the photoreceptor response of shaded plants.

Since more than half of the plant life on the earth is underwater, it is worthy of note that light scattering and absorption by water itself and by dissolved molecules or suspended particles can alter light quality underwater. For example, at depths of one to five meters, water may have strong absorption bands at 730 nm (FR) and in the near IR. Thus, with increasing depths, radiation is effectively 'compressed' into a narrower band of wavelengths toward the lower end of the PAR, often peaking near 500 nm. Large increases in R:FR can occur with depth underwater. Shading vegetation, however, can greatly reverse this trend within a water column.

Diurnal fluctuation at dawn and dusk, densities, heliotrophic movements and orientations of plant canopies and underwater attenuation are the primary natural modifiers of light quality. Since surprisingly large amounts of light may penetrate some soils to depths of seed germination and seedling growth, it may be worth noting that the predominant impact of soil on light quality is a substantial attenuation of B and a decrease in R/FR.

FILTERING OF RADIATION

Sheltered plant environments such as controlled environment chambers and greenhouses filter radiation by virtue of the lamps which they utilize and the materials from which they are constructed.

Spectral distributions of lamps generally provide poor duplication of solar radiation. Traditional combination use of fluorescent plus incandescent lamps in controlled environments typically provide no more than one-third the photosynthetic photon flux (PPF) levels of full sunlight. Various high-intensity discharge (HID) lamps can increase PPF levels in controlled environments. Barrier materials such as glass, Plexiglas (acrylic) and water are usually placed between the lamps and the growing area to provide ventilation of the lamp space for removal of heat. Bubenheim et al. (1988) observed that spectral compositions (in the 400 to 800 nm range) produced by any of several lamp types tested were not significantly changed by filtering through any of these barrier materials. The dry-tempered, 4 mm glass and the 5 mm Plexiglass single sheet filters reduced PPF 7%. Two layers of glass separated by a 50-mm air space reduced PPF by 14%. Both materials filtered longwave radiation more than shortwave. Plexiglas, which is opaque to ultraviolet radiation, reduced shortwave radiation more than glass and removed the 360 to 370 nm peak from a metal halide (MH) lamp. A 20 to 50 mm-layer of water above both materials reduced longwave radiation for all lamps. Water was by far the most effective filter for longwave radiation, reducing it to less than 10% of total incoming radiation. Unless other

pigments are involved, neither glass nor Plexiglas should influence photomorphogenesis because they do not appreciably alter light quality in the phytochrome action spectrum.

Greenhouse Construction and Shading Materials

McMahon et al (1990) investigated the spectral filtering properties of several greenhouse construction and shading materials used to reduce solar radiation reaching plants. Construction materials tested included single-layer glass, channelled, double-walled polycarbonate (untinted and tinted Lexan by General Electric Co.), channelled, double-walled acrylic (Exolite by Cyro), double-layered and inflated clear polyethylene films (Monsanto 602, 703 and Cloud-9 and 6-mil Fog-bloc by FVG-America, Inc.) and double-layered and inflated yellow polyethylene film (6-mil Fog-bloc by FVG-America, Inc.). All materials were new and clean. Radiation measurements were made with a LI-COR LI-1800 spectroradiometer equipped with a LI-1800-10 remote cosine sensor. Readings were made on cloudless, sunny days in the Spring at solar noon when the sun was near its zenith. Table 1 summarizes the percentage transmission of sunlight through different materials for photosynthetic photons (400-700) and photomorphogenic photons both blue (B) photons (400-500nm) and R/FR ratio (660/730). The listing of narrow-band R/FR ratios should be qualified as limited in ability to correlate consistently with all plant growth parameters and is shown for comparative purposes only (Rajapakse et al, 1992). At present, because of weaknesses of any phytochrome light quality designator (narrow-band R/FR, broad-band R/FR, or phytochrome photoequilibrium (ϕ)) to correlate consistently with observed plant responses, the presentation of complete spectral data over a frequency range is probably the most useful format. PPF transmission ranged from 95% through Exolite to 44% through tinted Lexan. Percentage transmission of B light were generally 3-10% lower than that of PPF light for all construction materials except glass where they were equal. The narrow-band R/FR ratio ranged from 0.95 for yellow Fog-bloc film to 1.03 for glass as normalized to 1.00 for unfiltered sunlight.

Shading materials (McMahon et al, 1990) tested included liquid compounds and solid screening products. The liquid compounds included white latex paint and Kool Ray green (Continenal Products Co., Euclid, OH). They were uniformly sprayed one time until close to runoff onto a piece of clean glass tilted to approximate the angle of a greenhouse roof. The screening products included the following: black, woven fabric (55% shade Chicopee, Inc.); black, knitted fabric (50% shade V-J Weathershade); vinyl coated polyester fabric with aluminized pigment (80% shade Enduro Silver by Handlee Enterprises); green vinyl coated polyester fabric (60 % shade Enduro Green by Handlee Enterprises); green, woven saran fabric (63% shade Chicopee Lumite) and Cravo LS-7 green polyester fabric (Cravo Ltd.). Table 2 summarizes photosynthetic and photomorphogenic light for the shading materials. Transmission properties varied appreciably for these shading materials. PPF reductions, however, were within 5% of manufacturer's specifications for all materials. Percentage transmission of full sun PPF ranged from 21% for Cravo LS-7 to 49% for V-J Weathershade. Unlike the construction materials, some shading materials transmitted a higher percentage of B light than PPF. For example, Cravo LS-7 transmitted 6% more B light than PPF as a percent of full sun. On the other hand, Kool Ray green compound transmitted only 7% of the B compared to 35% of the PPF, or 28% less B than PPF. The remaining shading materials transmitted from 0 to 3% less B than PAR. The

photomorphogenic R/FR ratio normalized to full sunlight (1.00) ranged from 0.94 to 1.06 for all shading materials except for 0.18 for Cravo LS-7 polyester fabric and 0.55 for Kool Ray compound.

TABLE 1. Spectral transmission properties of selected greenhouse coverings.

Material	Photosynthetic Light	Photomorphogenic Light	
	Photosynthetic Photon Flux (PPF) (400-700 nm) ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Blue Light (400-500 nm) ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Red/Far-red (660/730 nm)* Ratio
	% of full sun		Normalized to full sun
Sunlight	100	100	1
Glass	93	93	1.03
Monsanto 602	88	83	0.99
Monsanto 703	67	63	0.96
Monsanto Cloud-9	52	48	0.96
Fog-bloc 6 mil	68	64	1.02
Fog-bloc 6 mil, yellow	63	53	0.95
Exolite	95	92	0.98
Lexan	78	75	0.96
Lexan, tinted	44	38	0.96

Non-unity values for R/FR ratios of the construction and shading materials indicate alterations of light quality which could potentially modify growth of plants exposed to light transmitted through the materials. Some plant "stretching" may be attributed to reduced light under artificial shading, analogous to natural filtering in plant canopies. Altered light quality, however, will

TABLE 2. Spectral transmission properties of selected nursery and greenhouse shading materials.

Material	Photosynthetic Light	Photomorphogenic Light	
	Photosynthetic Photon Flux (PPF) (400-700 nm) ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Blue Light (400-500 nm) ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Red/ Far-red (660/730 nm)* Ratio
	% of full sun		Normalized to full sun
Sunlight	100	100	1
Kool Ray	35	7	0.55
Paint	41	39	1.01
Chicopee	45	44	1
V-J Weathershade	49	49	1.01
Enduro Silver	21	18	0.94
Enduro Green	42	40	1.06
Chicopee Lumite	35	34	0.96
Cravo LS-7	21	27	0.18

*Any current phytochrome light quality designator (narrow-band R/FR, broad-band R/FR, or phytochrome photoequilibrium (ϕ)) fails to correlate consistently with observed plant responses. The presentation of complete spectral data over a frequency range is probably the most useful format, if available.

also probably elongate internodes and cause greater plant heights. Phytochrome modifications in growth patterns might be particularly expected under Cravo LS-7 and Kool Ray shading materials. Moreover, the B light filtering characteristics of materials like yellow Fog-bloc polyethylene construction film and Cravo LS-7 green fabric and Kool Ray compound shading materials could potentially alter both photosynthetic and photomorphogenic activity in plants.

A further observation by McMahon et al (1990) was that the construction and shading materialscould be grouped as *non-selective* and *selective* filters over the radiation spectrum. The neutrally colored (black, white and silver) shading materials characteristically transmitted all wavelengths uniformly (non-selectively) as illustrated by the percent spectral transmission plot in Figure 2 for V-J Weathershade knitted black shade fabric over 400 to 850 nm. In contrast, the construction materials and the green shading materials were variable (selective) filters as illustrated in Figure 3 for percent spectral transmission with Kool Ray shading compound.
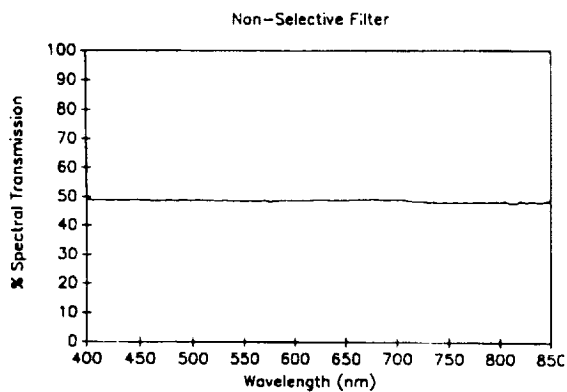

Figure 2. Example of a non-selective filter using spectral transmission values for V-J Weathershade 50% knitted black shade cloth. (McMahon et al, 1990)
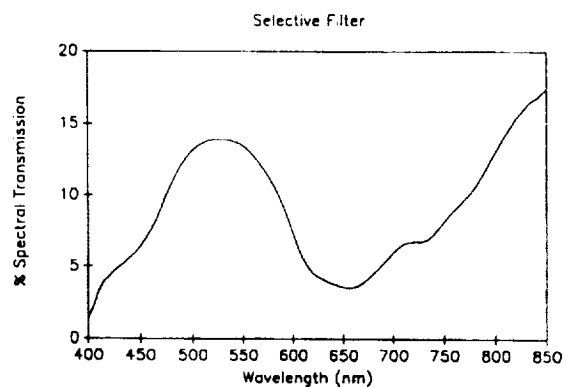
Figure 3. Example of a selective filter using spectral transmission values for Kool Ray green shading compound. (McMahon et al, 1990)

Channelled Plastic Fluid-Roof Filters

Channelled, double-walled acrylic and polycarbonate plastic greenhouse glazings have provided the opportunity to use water or liquid dyes as filtering materials contained in the hollow channels of the glazing. These filters have been variously called liquid optical filters (LOF), optical liquid filters (OLF), liquid radiation filters (LRF) and liquid spectral filters (LSF). They can both filter out infrared rays (heat) while transmitting PPF and can with colored liquids selectively transmit various parts of the electromagnetic spectrum to influence plant development.

In the 1970's, French scientists investigated and patented both double-layered acrylic and glass structures with fluid flowing within an enclosure between glazing layers (Chiapale et al, 1977; Chiapale et al, 1978). They used water and copper chloride ($CuCl_2$) in a closed loop flow as well as water over infrared absorbing glass as a lower layer. Their primary interests were modelling energy balances. They experienced reductions in earliness and yield with tomatoes, probably because of limited biological considerations for depressed CO_2 levels in atightly closed

environment. In the early 1980's, American, French, Canadian and Israeliscientists conducted further studies utilizing channelled plastic sheets (Benschop et al, 1980; van Bavel et al, 1981; Chiapale, 1981; Weichman, 1981; Sadler, 1983; Sadler and van Bavel, 1984; Tross et al, 1984). Benschop et al (1980) confirmed the earlier observations of Chiapale et al (1977) that circulating aqueous $CuCl_2$ absorbed infrared radiation. Simulation models of energy flow in the plastic fluid-roof greenhouses by van Bavel et al (1981), in collaboration with Chiapale et al (1983), predicted 20-40% reductions in heating requirements and virtual elimination of the need for forced ventilation. In experiments at College Station, TX, predictions of the model were confirmed. A later dynamic simulation model by Sadler and Van Bavel (1984) predicted various temperatures in the plastic fluid-roof greenhouse within 2-3°C and net radiations within 20-30 W m^{-2}. Tross et al (1984) confirmed close approximations of his model of an optical liquid filter (OLF) channelled polycarbonate fluid-roof greenhouse with a triangular, prism-shaped structure. A patent for specific copper chloride solutions intended for fluid-roof applications was issued in 1988 (Navon and Gan, 1988). For a number of years, scientists (Kopel et al, 1991; Levi et al, 1991; Zeroni et al, 1991) have been investigating plant culture in a full-scale (330 m^2), channelled polycarbonate LRF greenhouse in the Negev Desert in Israel. They were able to reduce temperatures sufficiently within the greenhouse to practice daylong CO_2 fertilization except for a few midday hours in mid-summer when ventilation was necessary. In addition to circulating aqueous $CuSO_4$, the Negev project has claimed, yet not disclosed for proprietary reasons, a less noxious fluid dye. Pollock et al (1992) established temperature profiles over the length of a 9.8-m long by 8-mm thick channelled polycarbonate panel for various steady-state combinations of flow rate and inlet temperature of circulating $CuSO_4 \cdot 5H_2O$ aqueous solutions. The primary factor for efficient cooling of a fluid-roof panel was adequate fluid flow rate.

Selective filtering of light primarily to influence photomorphogentic responses of plants was demonstrated in Norway in both solar-exposed growth chambers and a production greenhouse using green (#1358), red (#1409 Tetrazine) and yellow (#14123 Red 2G) dyes (all from D. F. Anstead Ltd.) and 2.5% $CuSO_4$ in channelled acrylic sheets (Mortensen et al, 1987; Mortensen and Stromme, 1987). Neutral shading was used so that the PPF levels were similar at all

Figure 4. Light transmission of water with different dyes in the range 350 to 900 nm wavelength, pure water; ▲ , blue; O, green; △ , yellow; *, red. (Mortensen et al., 1987)

light qualities. The light transmission properties of these aqueous filters are shown in Figure 4. (Ciba-Geigy # 178) that filtered out much R but not FR and 16% w/v $CuSO_4 \cdot 5H_2O$ which filtered more FR than R light. Neutral shading was used to get constant PPF levels (about 40-45% PPF reduction) with each filter. Figure 5 summarized the light transmission properties of the liquid filters tested at Clemson. Table 3 compares the broad band (R=600-700 nm; FR=700-800 nm) R/FR ratios for the liquid spectral filters used by the Norwegian and Clemson investigators and lists the narrow band (R=655-665 nm; FR=725-735 nm) R/FR ratios for the Clemson filters.
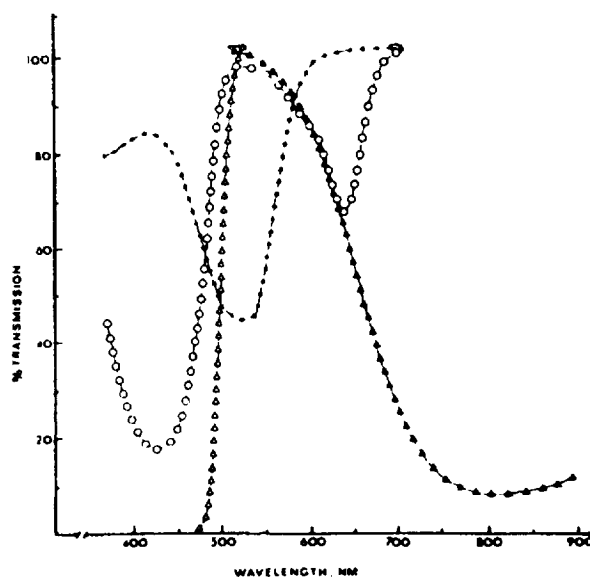
Plant Responses to Spectral Filters

Mortensen and Stromme (1987) observed that the blue $CuSO_4$ filter (high R/FR ratio) reduced dry weight in chrysanthemum (*Chrysanthemum x morifolium* Ramat.), tomato (*Lycopersicon esculentum* Mill.) and lettuce (*Lactuca sativa* L.) compared to natural sunlight and green, yellow and red filters. Plant heights for chrysanthemum and tomato were reduced by the $CuSO_4$ filter and increased by the green and yellow filters compared to natural light. In all species except poinsetta (*Euphorbia pulcherrima* Willd.), leaf area was significantly reduced by $CuSO_4$. Green and yellow filters increased leaf area in tomato compared to natural light. Lateral bud breaks were stimulated by the $CuSO_4$ filter in chrysanthemum and tomato, but inhibited by green and yellow filters in tomato. $CuSO_4$ filters led to dark green leaves while green and yellow filters caused light green leaves in chrysanthemum, tomato and lettuce. Light quality was similar in three experiments at decreasing PPF levels over the period from July to October.

McMahon et al, (1991) observed that two species of chrysanthemum (*Dendranthema x grandiflorum* (Ramat.) 'Spears' and 'Yellow Mandalay') grown under $CuSO_4$ filters had reduced heights, reduced internode lengths and increased chlorophyll content compared to controls grown under water- and/or air-filled channelled panels. Reduced B light with the red dye decreased chlorophyll content of pinched plants. Pinched plants under $CuSO_4$ filters and long days developed fewer nodes than controls because of the formation of abnormal capitula. Controls and unpinched plants from the other light treatments developed more nodes before forming similar abnormal capitula. Stem diameters and leaf areas did not differ among light treatments.

TABLE 3. Broad and narrow band R/FR ratios for various liquid spectral filters used by Norwegian and Clemson investigators.

Country	Filter	R/FR Ratio[*] Broad band[**]	R/FR Ratio[*] Narrow band[***]
Norway	Water	1.00	--
	$CuSO_4$(2.5%)	4.10	--
	Red	0.99	--
	Green	0.82	--
	Yellow	1.00	--
Clemson	Water	1.05	1.16
	Air	1.05	1.16
	$CuSO_4$(16%)	7.20	3.30
	Red	1.03	1.16
	Blue	0.70	0.99

* Any current phytochrome light quality designator (narrow-band R/FR, broad-band R/FR, or phytochrome photoequilibrium (ϕ)) fails to correlate consistently with observed plant responses. The presentation of complete spectral data over a frequency range is probably the most useful format, if available.

* R = 600-700 nm; FR = 700-800 nm

** R = 655-665 nm; FR = 725-735 nm

(Data from Mortensen and Stromme, 1987 and from McMahon et al, 1991)

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Further studies of the influence of liquid spectral filters on regulation of chrysanthemum by Rajapakse and Kelly (1992) utilized 4, 8 and 16 % (w/v) $CuSO_4 \cdot 5H_2O$ filters in channelled polycarbonate panels. These filters reduced PPF from natural irradiance inside a greenhouse (average ≈ 950 μmol m^{-2} s^{-1}) by 26, 36 and 47 %, respectively. Control treatments were shaded with plastic shade cloth to insure equal PPF with the $CuSO_4$ filters. Following a 4-week experimental period, average plant heights were approximately 40% shorter and average internode lengths were 34% shorter than those of control plants. Reductions in plant heights and internode lengths were observable within one week after initiation of the experiments. Total leaf area was reduced by 32% and leaf size by 24% under the $CuSO_4$ filters. Specific leaf weight (leaf fresh weight/leaf area), however, was greater under $CuSO_4$ filters than under the control treatment, indicating thicker leaves. Other observations under $CuSO_4$ filters were that fresh and dry leaf weights decreased by 30% and fresh and dry stem weights decreased by 60%, resulting in increased relative dry matter accumulation into leaves and reduced accumulation in the stems.

A similar study by Rajapakse and Kelly (1991) sought to determine the involvement of gibberellins in regulation of plant height under $CuSO_4$ filters. Using 6% $CuSO_4$ filters which reduced average PPF by about 34%, they evaluated the response of chrysanthemum to GA_3 and daminozide. Weekly applications of GA_3 increased plant height under both the $CuSO_4$ and control filters, but by about 20% greater under the $CuSO_4$ than under the control filter. Daminozide, a GA inhibitor, reduced plant height under both filters, but more under the control filter. Under both filters, plant height reduction caused by daminozide was prevented by GA_3 application. It appears that GA_3 may be partially involved in plant height reduction under $CuSO_4$ filters.

Rajapakse and Kelly (1993) also observed with the same species of chrysanthemum that, after 28 days, cumulative transpirational water loss of plants under $CuSO_4$ filters was approximately 37% less than of control plants under water-filled panels. Expressed as transpiration rates per leaf area, however, plants under both filters responded similarly, suggesting that the reduced cumulative water loss was a result of smaller plant sizes under $CuSO_4$ filters. Plants grown under $CuSO_4$ filters had slightly lower (10%) stomatal density than control plants. The size of individual stomata were not altered by the $CuSO_4$ filter, yet total number of stomata and total stomatal pore area per plant was about 50% less in plants grown under $CuSO_4$ filters because of less leaf area. Results such as these suggest that altering light quality might reduce water use and fertilizer demands in addition to controlling growth of plants in greenhouse production.

In similar studies using the same liquid spectral filters with miniature roses (*Rosa x hybrida* 'Meirutral'), McMahon and Kelly (1990) noted that plants were significantly shorter (25 to 35%) and had higher leaf chlorophyll (20 to 25%) when grown under the $CuSO_4$ filters (high R/FR ratio). Light quality treatments, however, did not affect the number of flower buds or the number of buds showing color. Differences in plants grown under filters deficient in B light or low in R/FR ratio were not observable, indicating that these light quality alterations were less influential in morphology of 'Meirutral' pot roses. Modifications of plant morphologies for both roses and chrysanthemum, as well as unpublished results with exacum, geranium and poinsetta were observed by McMahon and Kelly (1990) to be comparable to morphologies of compact, attractive, dark green plants being widely achieved commercially by the application of chemical growth regulators such as butanedioic acid mono (2,2-dimethylhydrazide), daminozide, B-Nine, Alar and uniconazole. The use of daminozide on edible crops has already been prohibited, and its use on other greenhouse crops is being continually scrutinized. Manipulation of light quality

to control plant morphology could be an attractive, natural alternative to chemical grouth regulators.

Rajapakse and Kelly (1994) also investigated the influence of spectral filters on the postharvest quality of potted miniature roses (*Rosa x hybrida* 'Meijikatar'). Again they observed that $CuSO_4$-filtered light significantly reduced plant height and internode length and increased the number of lateral shoots. Some seasonal variability was observed, however. $CuSO_4$ filters slightly accelerated flowering in early spring but slightly delayed flowering in late spring and summer. Total numbers of flowers were unaffected but the sizes of flowers were increased by $CuSO_4$ filters. Leaf sucrose and starch concentrations were reduced by 40% and 65%, respectively, while leaf glucose and fructose concentrations were unaffected by $CuSO_4$ filters. Plants grown under $CuSO_4$ filters had slightly more yellow leaves than control plants after shipping at 4 or 16°C. This response is probably a result of reduced carbohydrate status.

Rajapakse et al (1993) also investigated the responses of chrysanthemums (*Dendranthema x grandiflorum* (Ramat.) 'Spears and 'Bright Golden Anne') to end-of-day (EOD) R and FR exposures. At the end of 9-h light exposure inside a greenhouse, plants grown under $CuSO_4$ filters were exposed to either a R- or FR-light treatment of 15 minutes before being placed in a 15-h dark period. The R-light treatment was obtained inside a specially designed treatment box with 2.1 W m^{-2} in the 600-700 nm range obtained from six 40-W cool white fluorescent bulbs filtered through a Roscolux No. 19 acetate filter (Rosco, Port Chester, NY). Similarly, the FR treatment was obtained with 12.0 W m^{-2} in the 700-800 nm range obtained from two internal reflector incandescent bulbs filtered through a polyacrylic sheet of cast acrylic No. 2711 dark red filter (Rohm and Haas, Bristol, PA). EOD light treatments were given for 21 consecutive days. Non-EOD-treated plants remained in the growth chambers and were covered with black cloth during the 15-h dark periods. As observed in other experiments, light through $CuSO_4$ filters significantly reduced plant height, internode length and stem dry weight. Exposure to EOD-FR reversed the reduction of plant height, internode length and stem dry weight by $CuSO_4$ filters to a level comparable with plants receiving no EOD treatment. EOD-R treatment reduced plant height and stem dry weight of 'Bright Golden Anne' plants grown under the control filter, but had no effect under the $CuSO_4$ filter. EOD-FR treatment did not significantly alter plant height and stem dry weight under the control filters. In 'Spears' plants, EOD-R reduced stem dry weight under control filters but did not reduce stem or internode elongation. These results suggest that phytochrome may be involved in controlling plant response under the $CuSO_4$ filter. There is evidence, however, to suggest that an additional mechanism may be influencing stem and internode elongation.

Additional, non-liquid spectral filter experiments at Clemson have investigated EOD-R and -FR treatments of watermelon (*Citrullus lanatus* (Thunb.) Matsum & Naki cv.Sugar Baby) and tomato (*Lycopersicon esculentum* Mill. cv. Mountain Pride). Decoteau and Friend (1991) used the same R- and FR-treatment chambers with acetate and acrylic filters described earlier to treal 2-week old (two true leaf stage) watermelons. After four days of EOD-FR treatment, petiole lengths were longer and the angle between petioles more acute than in plants treated with EOD-R or non-EOD treated (control) plants. The EOD-FR promotion of internode length, petiole angle and petiole elongation was reversible by immediately following the FR with R light, implicating phytochrome involvement in growth regulation of watermelon. Plants treated 21 days with EOD light and subsequently grown 14 days without EOD treatment exhibited no residual EOD light effects on internode elongation as compared to plants receiving no EOD light treatments. Two-week pretreatments of tomatoes with EOD-R light before placement in a

greenhouse under ambient light conditions increased the number of flowers before the first harvest but had no effect on subsequent fruit production as compared with plants receiving similar FR-light treatments or no EOD treatments (Decoteau and Friend, 1991). In a second experiment with tomatoes when cool white fluorescent lights (high in R) were used to supplement natural light in an unshaded greenhouse for one hour before the end of the natural photoperiod, Decoteau and Friend found reduced plant height and total leaf length but no subsequent influence on fruit production when transplanted into the field. The supplemental R light (as provided by the fluorescent bulbs) probably affected plant growth by nullifying the EOD reduction in R/FR associated with the end of the daylight. These EOD treatments of plants suggest that light manipulation in the greenhouse may not need to be performed throughout the entire daylight period, but rather may be performed only for short intervals at the end of the daylight period.

SUMMARY

Research to date suggests that spectral filtering can be an effective alternative to chemical growth regulators for altering plant development. If properly implemented, it can be non-chemical and environmentally friendly. The aqueous $CuSO_4$ and $CuCl_2$ solutions in channelled plastic panels have been shown to be effective filters, but they can be highly toxic if the solutions contact plants. Some studies suggest that spectral filtration limited to short EOD intervals can also alter plant development.

Future research should be directed toward confirmation of the influence of spectral filters and exposure times on a broader range of plant species and cultivars. Efforts should also be made to identify non-noxious alternatives to aqueous copper solutions and/or to incorporate these chemicals permanently into plastic films and panels that can be used in greenhouse construction. It would also be informative to study the impacts of spectral filters on insect and microbal populations in plant growth facilities. The economic impacts of spectral filtering techniques should be assessed for each delivery methodology.

REFERENCES

Benschop, K., H. A. Spencer, E. W. Toop and F. L. Weichman. The well tempered greenhouse. Proceedings of the Joint Solar Conference , Solar Energy Society of Canada and the Pacific Northwest Solar Energy Association (Solwest 80), pp. 410-414. University of British Columbia, Vancouver, BC.

Bubenheim, D. L., B. Bugbee and F. B. Salisbury. 1988. Radiation in controlled environments: influence of lamp type and filter material. Jour. Amer. Soc. Hort. Sci. 113(3):468-474.

Chiapale, J. P., J. A. Damagnez and P. M. Denis. 1977. Modification of a greenhouse environment through use of a collecting fluid. Proceedings of the International Symposium on Controlled-Environment Agriculture. University of Arizona, Tucson, AZ.

Chiapale, J. P., J. A. Damagnez, P. M. Denis and P. Jourdan. 1978. Method and an installation for the air-conditioning of greenhouses and frames. U. S. Patent No. 4,108,373.

Chiapale, J. P. 1981. Le Serre Solaire INRA-CEA: Resultats Physiques. Acta Horticulturae Issue 115:387-400.

Decoteau, D. R. and H.H. Friend. 1991. Phytochrome-regulated growth of young watermelon plants. Jour. Amer. Soc. Hort. Sci. 116(3):512-515.

Decoteau, D. R. and H.H. Friend. 1991. Growth and subsequent yield of tomatoes following end-of-day light treatment of transplants. HortScience 26(12)1528-1530.

Decoteau, D. R., H. A. Hatt, J. W. Kelly, M. J. McMahon, N. Rajapakse, R. E. Young and R. K. Pollock. 1993. Applications of photomorphogenesis research to horticultural systems. HortScience 28(10)974,1063.

Hughes, J. E., D. C. Morgan, P. A. Lambton, C. R. Black and H. Smith. 1984. Photoperiodic time signals during twilight. Plant Cell and Environment 7:269-277.

Kasperbauer, M. J. 1987. Far-red light reflection from green leaves and effects on phytochrome-mediated assimilate partitioning under field conditions. Plant Physiology 85:350-354.

Kopel, R. J. Gale, M. Zeroni and S. Levi. 1991. A greenhouse with selective radiation filtering under desert conditions. International Proceedings on Applied Technology of Greenhouses, Beijing, China. October 7-10, 1991.

Levi, S., M. Zeroni, J. Gale and R. Kopel. 1991. Development of liquid radiation filters for use in greenhouses. International Proceedings on Applied Technology of Greenhouses, Beijing, China. October 7-10, 1991.

McMahon, M. J. and J. W. Kelly. 1990. Influence of spectral filters on height, leaf chlorophyll and flowering of *Rosa x hybrida* 'Meirutral'. Jour. Environ. Hort. 8(4):209-211.

McMahon, M. J., J. W. Kelly and D. R. Decoteau. 1990. Spectral transmission of selected greenhouse construction and nursery shading materials. J. Environ. Hort. 8(3):118-121.

McMahon, M. J., J. W. Kelly, D. R. Decoteau, R. E. Young and R. K. Pollock. 1991. Growth of *Dendranthema x grandiflorum* (Ramat.) Kitamura under various spectral filters. Jour. Amer. Soc. Hort. Sci. 116(6):950-954.

Mortensen, L. M. and E. Stromme. 1987. Effects of light quality on some greenhouse crops. Scientia Horticulturae 33:27-36.

Mortensen, L. M., E. Stromme, Z. Sebesta and D. Wenner. 1987. Growth chambers with control of light quality. Norwegian Journal of Agricultural Sciences 1:1-5.

Navon, G. and Gan. 1988. Liquid optical filter and method for the near infrared light. U. S. Patent No. 4,717,220.

Pollock, R. K., R. E. Young, J. M. Bunn and W. H. Allen. 1992. Cooling characteristics of a fluid-roof panel. ASAE Paper No. 92-4074. ASAE, St. Joseph, MI.

Rajapske, N. C. and J. W. Kelly. 1991. Influence of $CuSO_4$ spectral filters, daminozide and exogenous gibberellic acid on growth of *Dendranthema x grandiflorum* (Ramat.) Kitamura 'Bright Golden Anne'. Jour. of Plant Growth Regulation 10:207-214.

Rajapske, N. C. and J. W. Kelly. 1992. Regulation of Chrysanthemum growth by spectral filters. Jour. Amer. Soc. Hort. Sci. 117(3):481-485.

Rajapske, N. C., R. K. Pollock, M. J. McMahon, J. W. Kelly and R. E. Young. 1992. Interpretation of light quality measurements and plant response in spectral filter research. HortScience 27(11):1208-1210.

Rajapske, N. C. and J. W. Kelly. 1993. Spectral filters influence transpirational water loss in Chrysanthemum. HortScience 28(10):999-1001.

Rajapske, N. C., M. J. McMahon and J. W. Kelly. 1993. End of day far-red reverses height reduction of Chrysanthemum induced by $CuSO_4$ spectral filters. Scietia Horticulturea 53:249-259.

Rajapske, N. C. and J. W. Kelly. 1994. Influence of spectral filters on growth and postharvest quality of potted miniature roses. Scietia Horticulturae 56:245-255.

Sadler, E. J. 1983. Simulation of the energy, carbon and water balance or a fluid-roof greenhouse. PhD. Dissertation, Texas A & M University, College Station, TX.

Sadler, E. J. and C. H. M. van Bavel. 1984. Simulation and measurement of enery partitioning in a fluid-roof greenhouse. Agricultural and Forestry Meteorology 33:1-13.

Smith, H. 1986. The perception of light quality. In Photomorphogenesis in Plants, Editors, R. E. Kendricks and G. H. M. Kronenberg. Martinus Nijhoff Publishers, Dordrecht, Netherlands. Pp 187-217.

Smith, H. 1992. Light quality, photoperception and plant strategy. Annual Review of Plant Physiology 33:481-518.

Tross, M. J., D. Degani, A. Ziv and R. Kopel. 1984. An optical liquid filter greenhouse: numerical solution and verification of a thermodynamic model. Acta Horticulturae, Issue 148:401-409.

Van Bavel, C. H. M., J. Damagnez and E. J. Sadler. 1981. The fluid-roof solar greenhouse: energy budget analysis by simulation. Agricultural Meteorology 23:61-76.

Weichman, F. L. 1981. Channelled plastic for greenhouses and skylight use. Solar Energy 27(6):571-575.

Zeroni, M., J. Gale, R. Kopel and S. Levi. 1991. Agrotechniques for a closed greenhouse with a radiation filtering roof. International Proceedings on Applied Technology of Greenhouses, Beijing, China. October 7-10, 1991.