Reviews

Plant Height Control by Photoselective Filters: Current Status and Future Prospects

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SUMMARY. The interest in using nonchemical alternatives for growth control of horticultural crops has recently increased due to public concerns for food safety and environmental pollution. Several research teams around the world are investigating alternative growth control measures, such as genetic manipulation, temperature, water and nutrient management, mechanical conditioning, and light quality manipulation. This review discusses the recent developments in light quality manipulation as a nonchemical alternative for greenhouse plant height control.

Height control of greenhouse crops is an important practice to optimize efficient handling and rapid establishment in the field. Many techniques are available, but chemical height control has been the standard practice in commercial operations. Because of potential health risks to consumers and concerns of environmental pollution, the Food and Drug Administration (FDA) and the Environmental Protection Agency (EPA) have imposed restrictions on the use of growth regulating chemicals in agriculture. Use of daminozide (Alar), once the primary chemical used for controlling vegetable transplant height has been banned in the United States. As a result, no chemical growth regulators are currently labeled for height control of vegetable transplants in the United States. Growers in other countries are facing similar restrictions on using chemical growth regulators on food crops. Several research teams around the world are investigating alternative height control measures, such as gene manipulation (Jordan et al., 1995; Kusaba et al., 1998; Tennessen et al., 1997), greenhouse temperature management (Erwin and Heins, 1995; Heins and Erwin 1990; Moe et al., 1992), mechanical conditioning (Latimer, 1991; Latimer and Beverly, 1993), and light quality manipulation (Mortensen and Stromme, 1987; Rajapakse and Kelly, 1992;). The objective of this paper is to discuss the recent developments in light quality manipulation as a nonchemical alternative for greenhouse plant height control.

Light and plant growth

Plants have specialized pigment systems that can capture radiant energy in different regions of the electromagnetic spectrum. For example, photosynthetically active radiation (400–700 nm), captured by chlorophyll pigments, provides the energy for photosynthesis, the process by which plants combine carbon dioxide and water to produce oxygen and carbohydrates. Carbon assimilated during photosynthesis provides the energy to sustain life on earth.

Light also acts as a signal of environmental conditions surrounding the plants. There are photoreceptors that function as signal transducers to provide information that controls physiological and morphological responses. Through these pigments, plants have the ability to perceive subtle changes in light composition for initiation of physiological and morphological changes. This ability of light to control plant morphology is independent of photosynthesis and is known as photomorphogenesis. In photomorphogenesis, photons in specific regions of the spectrum are perceived by the photoreceptors present in smaller quantities. Known photomorphogenic receptors include phytochrome (the red and far-red light sensor that has absorption peaks in red and far-red regions of the spectrum, respectively) and cryptochrome (the hypothetical UV-B and blue light sensor).

Phytochrome is the most intensively studied sensory pigment that controls photomorphogenesis. Phytochrome is capable of detecting wavelengths from 300 to 800 nm with maximum sensitivity in red (R, 600 to 700 nm with peak absorption at 660 nm) and far-red (FR, 700 to 800 nm with peak absorption at 730 nm) wavelengths of the spectrum. This pigment system consists of two interconvertible forms: the P_r form absorbs red light and upon absorption is transformed into the P_{fr} form which absorbs far-red light and is transformed into the P_r

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form. Of the two forms, the P_{fr} form is assumed to be the active form that controls signal transduction and plant response.

Photon ratios between the red and far-red region of the spectrum (R:FR ratio) and *in vitro* estimates of phytochrome photoequilibrium (ϕ) [amount of phytochrome in the P_{fr} form relative to total phytochrome (P_{fr}:P_{tot} at photoequilibrium)] have been commonly used to quantitatively describe the phytochrome-mediated responses such as stem elongation. In general, ϕ depends largely on the absorption of red and far-red wavelengths by the plant and therefore, ϕ decreases with decreasing R:FR ratio. Smith and Holmes (1977) reported that a hyperbolic relationship exists between R:FR ratio and ϕ indicating that a small change in R:FR ratio can result in a large change in ϕ in the natural environment. Morgan and Smith (1976 and 1979) reported that the stem elongation rate and height of range of herbaceous plants were inversely proportional to the ϕ (i.e., higher the ϕ shorter the plant). Therefore, by manipulating the red and far-red light in the greenhouse to establish a high ϕ, height of greenhouse crops can be controlled with minimum chemical applications.

Greenhouse light quality manipulation can be achieved either with supplemental electric lighting systems with relatively high red and low far-red light or by spectral filters that can alter red and far-red light balance of sunlight. Incandescent lamps, which are low in R:FR ratio, frequently lead to stem elongation while fluorescent sources, which are high in R:FR ratio, produce short and compact plants. Radiation filters, both liquid and rigid, for improving greenhouse crop productivity and reducing greenhouse temperature have gained attention in 1970s and considerable progress has been made since then (Kadman-Zahavi et al., 1976; Novoplansky et al., 1990).

Spectral filters

GREENHOUSE CONSTRUCTION AND SHADING MATERIALS. Light transmission by greenhouse construction and shading material can be segregated into two categories, nonselective and selective. Nonselective material transmits all wavelengths uniformly while the selective material transmits wavelengths disproportionately. McMahon et al. (1990) investigated the spectral transmission of several commercially available greenhouse construction and shading materials used to reduce solar radiation. Table 1 summarizes the percentage transmission of photosynthetic photon flux (PPF) and photomorphogenic light (blue photons and R:FR ratios) through different materials. PPF transmission ranged from 95% through Exolite (Cryo Industries, Mt. Arlington, N.J) to 44% through tinted Lexan (General Electric Co., Cleveland, Ohio). Percentage transmission of blue light was similar but generally 3% to 10% lower than that of PPF. Red:far-red ratio ranged from 1.03 for glass to 0.95 for Fog-bloc yellow (FVG-America, Inc., Minneapolis, Minn.). Shade materials varied greatly in light transmission properties (Table 2). PPF transmission ranged from 21% in Eudoro Silver (Handlee Enterprises, Houston, Texas) to 49% in V-J Weathershade (V-J Weathershade, Apopka, Fla.). Red:far-red ratio ranged from 1.06 in Enduro Green (Handlee Enterprises, Houston, Texas) to 0.18 in Cravo LS-7 (Cravo, Ltd. Bramford, Ontario, Canada). Unlike the construction materials, some shading materials transmitted a higher percentage of blue light than PPF. For example, Cravo LS-7 materials transmitted 6% more blue light than PPF while Kool Ray green (Continental Products Co., Euclid, Ohio) transmitted 28% more PPF than blue light. Alterations in the quality of light transmitted through the material suggest that the covering and shading materials can

Table 1. Spectral transmission properties of selected greenhouse coverings (McMahon et al., 1990).

Material	Transmission[z] (%) PPF	Transmission[z] (%) Blue light	R:FR[y]
Sun	100	100	1.02
Glass	93	93	1.03
Monsanto 602[x]	88	83	0.99
Monsanto 703[x]	67	63	0.96
Monsanto Cloud-9[x]	52	48	0.96
Fog-bloc (Clear)[w]	68	64	1.02
Fog-bloc (Yellow)[w]	63	53	0.95
Exolite[v]	95	92	0.98
Lexan[u]	78	75	0.96
Lexan, tinted[u]	44	38	0.96

[z] Photosynthetic photon flux (PPF; 400 to 700 nm) or blue light (400 to 500 nm) as percentage of full sun.
[y] Red:far-red (660:730 nm).
[x] Greenhouse film (Monsanto, Inc., St. Louis, Mo.)
[w] Polyethylene (FVG-America, Inc., Minneapolis, Minn.)
[v] Chanelled, double-walled acrylic (Cryo Industries, Mt. Arlington, N.J.)
[u] Chanelled, double-walled polycarbonate (General Electric Co., Cleveland, Ohio)

Table 2. Spectral transmission properties of selected nursery and greenhouse shading materials (McMahon et al., 1990).

Material	Transmission[z] (%) PPF	Transmission[z] (%) Blue light	R:FR[y]
Sun	100	100	1.02
Kool Ray[x]	35	7	0.55
Chicopee[w]	45	44	1.00
V-J Weathershade[v]	49	49	1.01
Enduro Silver[u]	21	18	0.94
Enduro Green[u]	42	40	1.06
Chicopee Lumite[t]	35	34	0.96
Cravo LS-7[s]	21	27	0.18

[z] Photosynthetic photon flux (PPF; 400 to 700 nm) or blue light (400 to 500 nm) as percentage of full sun.
[y] Red:far-red (660:730 nm).
[x] Kool Ray green (Continental Products Co., Euclid, Ohio).
[w] Black woven fabric (Chicopee, Inc., Gainesville, Fla.).
[v] Black knitted fabric (V-J Weathershade, Apopka, Fla.).
[u] Vinyl coated polyester with aluminum pigment (Handlee Enterprises, Houston, Texas).
[t] Green woven saran fabric (Chicopee, Inc., Gainesville, Fla.).
[s] Green polyester fabric (Cravo, Ltd. Bramford, Ontario, Canada).

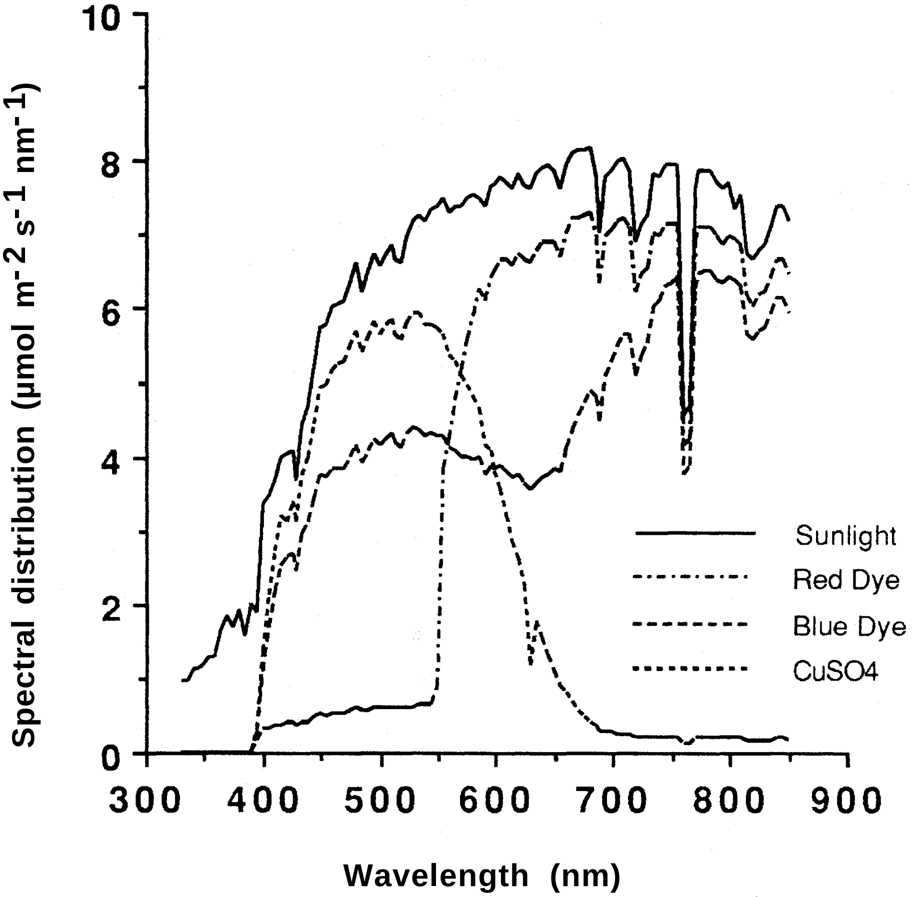

Fig. 1. Spectral distribution under liquid red dye (#259), blue dye #171 (CIBA-GEIGY, Greensboro, N.C.), and $CuSO_4$ filters (McMahon et al., 1991).

potentially modify growth of plants.

FLUID ROOF FILTERS. Channeled, double-walled acrylic and polycarbonate plastic greenhouse glazings allow liquid dyes to be contained in hollow channels of the glazing as filtering materials. In the 1970s and 1980s, liquid filters were widely investigated for filtering out infrared radiation (heat) from sunlight as a mean to cool greenhouses. Van Bavel et al. (1981) noted liquid radiation filters reduce energy requirements by 20% to 40% and virtually eliminate the need for forced ventilation in greenhouses. The ability of various aqueous dye filters [red, green, yellow, blue, and copper sulfate ($CuSO_4 \bullet 5H_2O$)] to selectively remove elongation-stimulating far-red light from the natural spectrum and to reduce plant height was investigated in the late 1980s in Norway (Mortensen et al., 1987) and in the USA (McMahon et al., 1990). Of the different liquid filters tested only liquid $CuSO_4$ filters were effective in removing elongation-stimulating far-red wavelengths from the sunlight (Fig. 1). The $CuSO_4$ liquid filter reduced both red and far-red wavelengths, but the reduction of far-red was greater than the reduction of red wavelengths thus, resulting in a high R:FR ratio and high ϕ.

Plant responses to liquid spectral filters

HEIGHT AND INTERNODE LENGTH. Mortensen and Stromme (1987) observed that only liquid $CuSO_4$ filters reduced plant height and internode length of chrysanthemum [*Dendranthema ×grandiflorum* (Ramat.) Kitamura], tomato [*Lycopersicon esculentum* Mill.], and lettuce [*Lactuca sativa* L.] plants. Green and yellow filters increased plant height of these crops compared to natural light. In chrysanthemum and tomato, lateral buds were stimulated by $CuSO_4$ filters but inhibited by green and yellow filters. McMahon and Kelly (1990) and McMahon et al. (1991) observed that poinsettia [*Euphorbia pulcherrima* Willd.] and two cultivars of chrysanthemum, ‘Spears’ and ‘Yellow Mandalay’, grown under $CuSO_4$ filters had reduced heights and internode lengths compared to control plants grown under natural light or water filters. A later study evaluated the influence of concentration of $CuSO_4$ (4%, 8%, and 16%) in the filter on the growth of ‘Bright Golden Anne’ chrysanthemums (Rajapakse and Kelly, 1992). Increasing the concentration of $CuSO_4$ in the filter from 4% to 16% reduced PPF by 26% to 47%, respec-

Table 3. Plant height reduction in response to $CuSO_4$ filtered light.

Positive response	No response
Ageratum (*Ageratum* L.)^z	Azalea^t
Easter lily^y	Tulip^t
Geranium (*Pelargonium* L’Herit)^z	Hyacinth^t
Poinsettia^{xw}	Narcissus^t
Impatiens (*Impatiens* Hook.)^z	
Lettuce^w	
Pansy (*Viola* L.)^z	
Chrysanthemum^{wv}	
Pepper^z	
Miniature roses^u	
Petunia (*Petunia* Vilm.-Andr.)^z	
Exacum (*Exacum* L.)^t	
Salvia (*Salvia* L.)^z	
Vinca (*Catharanthus* G. Don)^t	
Tomato^{zw}	
Marigold (*Tagetes* L.)^s	

^{z}Benson, 1992.
^{y}Kambalapally and Rajapakse, 1998.
^{x}McMahon and Kelly, 1990.
^{w}Mortensen and Stromme, 1987.
^{v}Rajapakse and Kelly, 1992.
^{u}Rajapakse and Kelly, 1994.
^{t}M. McMahon, unpublished data.
^{s}S. Li, unpublished data.

Table 4. Effect of dye concentration in dwarf type film on height control of chrysanthemum, bell pepper, and watermelon plants. The number followed by the film indicates the percentage transmission of photosynthetically active radiation (PAR). As the dye concentration increased PAR transmission decreased. Control is a polyethylene film without dye. Percentage height reductions compared to control plants are given in parentheses.

	Plant ht (cm)		
Material	**Chrysanthemum**[z]	**Bell pepper**[z]	**Watermelon**[y]
Control	29.7	22.1	28.4
Dwarf film-1 #85	26.6 (–10)	17.2 (–22)	21.7 (–24)
Dwarf film-1 #75	23.7 (–20)	13.9 (–37)	14.6 (–49)
Dwarf film-1 #65	20.9 (–30)	13.9 (–37)	14.5 (–49)
Dwarf film-1 #55	21.8 (–27)	12.0 (–46)	14.9 (–48)

[z] Rajapakse et al., 1998.
[y] D. Ranwala, unpublished data.

tively, compared to control. Average plant height and internode length were reduced by ≈35% regardless of the concentration, suggesting that concentrations as low as 4% $CuSO_4$ could be effectively used. Height reduction under $CuSO_4$ filters was caused mainly by the decrease in internode length, as the number of nodes was not altered. In all these studies, the PPF had been adjusted to be the same among all treatments.

In addition to height reduction, plants grown under $CuSO_4$ filters had more leaf chlorophyll, darker green leaves, and were compact than control plants similar to plants treated with chemical growth regulators (McMahon et al., 1991; Rajapakse and Kelly, 1992. Subsequent studies revealed that a wide range of plants respond to $CuSO_4$ filtered light (Table 3). Response varies with species and photoperiod. For example, in tomatoes, $CuSO_4$ filters reduced height by 30% to 35% (Mortensen and Stromme, 1987). Azalea (*Rhododendron* L.) and bulbs such as tulip (*Tulipa* L.), hyacinth (*Hyacinthus* L.), and daffodil (*Narcissus* L.) did not respond to $CuSO_4$ filtered light (Table 3). In chrysanthemums, $CuSO_4$ filtered light reduced height by ≈30% in short photoperiod-grown (fall and spring) plants but in long photoperiods (summer), plant height reduction was ≈20% (Rajapakse and Kelly, 1995). A similar response was observed with miniature roses [*Rosa* ×*hybrida* 'Meijikatar'] grown in short and long photoperiods (Rajapakse and Kelly, 1994).

Water use. Work with chrysanthemum 'Bright Golden Anne' indicated that plants grown under the $CuSO_4$ filter had 37% less cumulative water use than control plants (Rajapakse and Kelly, 1993). However, water loss rate per unit leaf area was similar between plants grown under $CuSO_4$ and control filters suggesting this reduction in cumulative water loss was due smaller plant size. Plants grown under the $CuSO_4$ filter had lower stomatal density compared to control plants. Light transmitted through the $CuSO_4$ filter did not alter the size of individual stomata. Total number of stomata and total stomatal pore area per plant was 50% less in plants grown under the $CuSO_4$ filter than those of control plants due to less leaf area.

Flower development. The influence of filtered light on flower development and flower quality varied with plant species, cultivar, and growing season. In 'Meijikatar' miniature roses, $CuSO_4$ filters slightly accelerated (2 to 3 d) anthesis of early spring grown plants but slightly delayed (2 to 3 d) anthesis of late spring- and summer-grown plants (Rajapakse and Kelly, 1994). In 'Bright Golden Anne' chrysanthemums, $CuSO_4$ filters delayed anthesis by 7 d in early fall-grown (September) plants and by 13 d in late fall-grown (December) plants (Rajapakse and Kelly, 1995). Spectral filters did not affect total number of flowers, but plants grown under $CuSO_4$ filters produced smaller flowers than control in both miniature roses and chrysanthemums. In 'Spears' chrysanthemums, McMahon et al. (1991) reported that $CuSO_4$ filters promoted earlier flowering under noninductive natural long days compared to control plants. However, under artificial short days, $CuSO_4$ did not affect the time to flower in 'Spears' chrysanthemums. In 'Nellie White' easter lilies [*Lilium longiflorum* Thunb.], $CuSO_4$ filters did not delay anthesis or reduce flower size (Kambalapally and Rajapakse, 1998).

Dry matter accumulation and partitioning. Total shoot dry weight of chrysanthemums decreased when plants were grown under $CuSO_4$ filters (Rajapakse and Kelly, 1995). Shoot dry matter partitioning was also affected by $CuSO_4$ filters; reduced stem dry matter accumulation and increased leaf dry matter accumulation. This suggests that the translocation of photosynthates may be affected by light quality under $CuSO_4$ filters. The dry weights per unit leaf area and the unit length of stem were reduced by light transmitted through the $CuSO_4$ filter.

Carbohydrate status. $CuSO_4$ filters also reduced both leaf and stem total soluble sugars (sucrose, glucose, and fructose) and starch concentrations in miniature roses and chrysanthemums (Rajapakse and Kelly, 1994 and 1995). However, the magnitude of reduction varied with the growing season; greater in spring than in fall. For example, $CuSO_4$ filters reduced leaf soluble sugar concentration by ≈54% in spring-grown chrysanthemum plants but only 29% in fall-grown plants. The reduction in carbohydrate pools may be a result of reduced photosynthesis or increased respiration of plants grown under $CuSO_4$ filters. Our preliminary work with chrysanthemums indicated that the rate of photosynthesis was lower in plants grown under $CuSO_4$ filters than under control filters but rate of respiration was not different (A. Tatenini, unpublished data).

Postharvest quality. The reduced carbohydrate levels of plants grown under $CuSO_4$ filters could lead to adverse effects on postharvest longevity. Work with miniature roses indicated that postharvest quality was reduced and leaf yellowing increased in plants grown under $CuSO_4$ filters compared to control plants (Rajapakse and Kelly, 1994). In Easter lilies and chrysanthemums, $CuSO_4$ spectral filters reduced flower shelf life by 3 to 4 d compared to control plants (Kambalapally and Rajapakse, 1998). Plants subjected to 4 °C (39 °F) storage for 1 week before being placed in an interior environment exhibited even less shelf life.

Physiological basis of light quality responses

Gibberellins (GAs) are a group of

plant growth hormones involved in a wide range of plant processes such as germination, cell division, cell elongation, flowering and fruit set and development. Endogenous gibberellins play an important role in the control of stem elongation and internode length (Dijkstra and Kuiper, 1989; Murfet, 1990; Ross et al., 1990). Chemical growth retardants reduce plant height by suppressing the production of natural gibberellins. We hypothesize that GA biosynthesis, or its action may be suppressed under $CuSO_4$ spectral filters because of similarities between the effects of chemical growth regulators and $CuSO_4$ spectral filters.

Stem elongation in response to changes in light quality may be mediated by changes in GA level (Campell and Bonner, 1986; Morgan et al., 1980) or sensitivity to GA (Reid and Ross, 1988). In efforts to understand the physiological basis for growth control by spectral filters, we applied 50 $mg{\cdot}L^{-1}$ (ppm) GA_3 (Pro-Gibb, Abbot Laboratories, Chicago, Ill.) on the first day of spectral filter treatment or weekly to chrysanthemum plants grown under control or $CuSO_4$ spectral filters (Rajapakse and Kelly, 1991). Both single and weekly applications of GA_3 reversed the plant height reduction caused by $CuSO_4$ filters, but the weekly applications were more effective than the single application. We also applied 3500 $mg{\cdot}L^{-1}$ of daminozide (B-Nine, Uniroyal Chemical Co. Inc., Middlebury, Conn.), a known gibberellin biosynthesis inhibitor, weekly to chrysanthemum plants grown under control and $CuSO_4$ filters (Rajapakse and Kelly, 1991). Daminozide treatment reduced plant height under both $CuSO_4$ and control filters but the effect was greatest under the control filter.

The level of GA-like substances in apical regions is known to be high in plants treated with far-red light (Tucker, 1976). Lockhart (1964) suggested that the conversion of GA to the active form might be inhibited by red light and promoted by far-red light. Campell and Bonner (1986) reported that 3β-hydroxylation of GA_{20} (inactive) to GA_1 (active) in dwarf pea seedlings is prevented by red light and controlled by phytochrome. Exposure to end-of-day far-red light reversed the reduction of plant height and internode length caused by the $CuSO_4$ filters to a level comparable with plants that received no end-of-day far-red treatment under control filters (Rajapakse et al., 1993). Exposure to end-of-day red light reduced height and internode length of chrysanthemum plants grown under control filters but had no effect under $CuSO_4$ filters. Exposure to end-of-day far-red did not significantly alter height and internode length under control filters. Observations with exogenous GA application and with end-of-day exposure to red or far-red light suggest that reduction of gibberellin levels by $CuSO_4$ filter may be, at least partially, responsible for plant height reduction.

Gibberellin biosynthesis is a complex process that involves several enzymes and intermediate gibberellins. Hedden and Kamiya (1997) have published an excellent recent review of GA biosynthesis. Although many have been identified to date, only GA_1, GA_3, GA_4, and GA_7 are active in regulating plant growth. GA_1 is the most active in regulating the vegetative growth in many crops. The current research focuses on quantifying the endogenous gibberellin levels (GA_{19}, GA_{20}, and GA_1) and on investigating the responses of spectral-filter-grown chrysanthemum plants to intermediate gibberellins (GA_{19} and GA_{20}) in the GA biosynthetic pathway. Our quantification studies indicate that GA_{19} levels (inactive) were higher and GA_1 (active) levels were lower in $CuSO_4$ filter grown plants than in control plants. The response of $CuSO_4$ filter grown plants to exogenous GA_{19} was lower than control plants (S. Maki, unpublished data). These preliminary observations suggest that the conversion of GA_{19} to GA_{20} may be reduced under the $CuSO_4$ filters.

Developments in photoselective greenhouse films and panels

Although research has demonstrated that light manipulation by liquid $CuSO_4$ filters have the potential for being a nonchemical alternative for height control of greenhouse plants, liquid spectral filter technology has a limited value to commercial growers because of difficulties in materials handling and of high initial construction costs. In addition, $CuSO_4$ is hazardous and can be phytotoxic in the event of spills.

For spectral filter technology to be acceptable commercially, an easy-to-handle plastic greenhouse cover-

Fig. 2. Spectral distribution of light transmitted through Mitsui photoselective films. SXE-4 is the film with red absorbing pigment (tall film). YXE-1 and YXE-10 are films with two types of far-red absorbing pigments (dwarf films). Control film is a polyethylene film without dye.

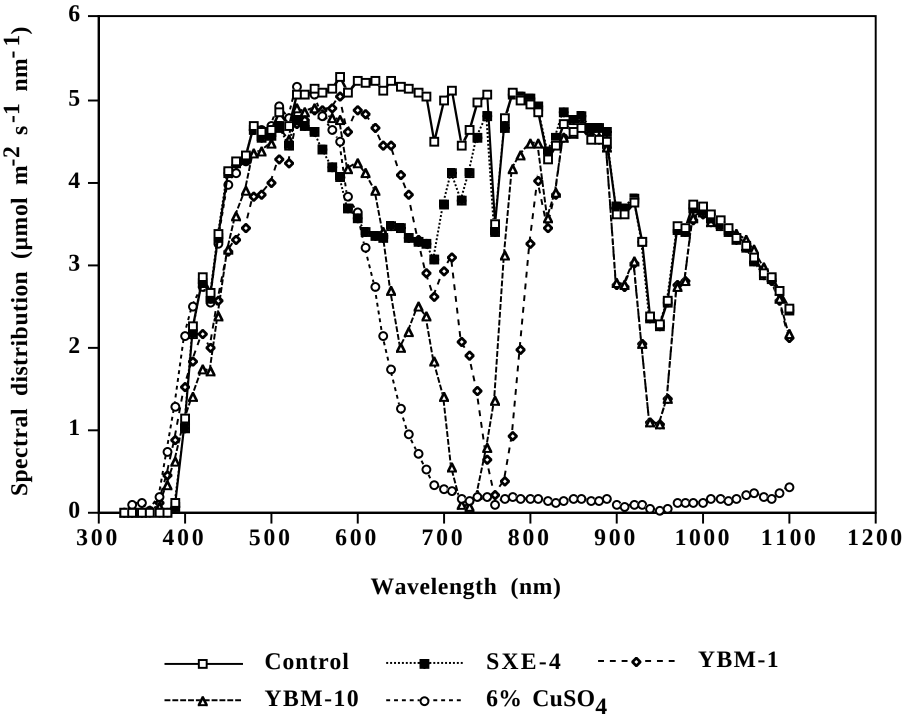

Table 5. Influence of red or far-red light intercepting plastic films (tall or dwarf films, respectively) on plant height. Number in parentheses indicates the percentage height compared to control plants. Control film is a polyethylene film without dye.

Crop	Plant ht (cm)[z] Control film	 Tall films	 Dwarf films
Vegetable			
Cucumber (*Cucumis sativus* L.)			
'Hokushin'[y]	44.0	62.5 (142)	28.1 (64)
'Sweet Success'[x]	17.3	19.8 (114)	11.1 (64)
Tomato			
'Saturn'[y]	57.8	65.1 (113)	48.5 (84)
'Mountain Pride'[x]	15.0	15.8 (106)	11.2 (75)
Turfed stone Leek (Allium wakegi Araki) 'Kiharabansei'[w]	35.0	34.5 (99)	34.7 (99)
Sunflower (*Helianthus annuus* L.) 'Russian Mammoth'[v]	23.5	29.0 (123)	15.0 (64)
Cabbage (*Brassica oleracea L.*) 'Suehiro Kanran'[v]	3.5	4.5 (129)	2.5 (71)
Kidney bean (*Phaseolus vulgaris* L.) 'Saberu'[u]	16.6	---	9.5 (57)
Bell pepper 'Capistrano'[t]	11.1	11.4 (103)	8.4 (76)
Ornamental			
Snapdragon (*Antirrhinum* L.).[s]	9.6	13.1 (136)	10.1 (105)
Verbena (*Verbena* L.)[s]	11.0	11.0 (100)	5.3 (48)
Petunia[s]	8.0	14.5 (181)	3.0 (38)
Delphinium (*Delphinium* L.)[s]	9.0	10.0 (111)	7.8 (87)
Chrysanthemum			
'Bright Golden Anne'[t]	25.1	---	18.5 (74)
'Iridon'[x]	15.9	---	9.8 (62)
'Yellow Snowden'[x]	35.4	---	26.6 (75)

[z] 2.54 cm=1.0 inch.
[y] Murakami et al., 1997.
[x] S. Li, unpublished data.
[w] Yamazaki et al., 1998.
[v] Murakami, et al., 1996.
[u] Oi et al., 1998.
[t] Rajapakse et al., 1998.
[s] Kumai et al., 1998.

ing or shading material with the ability to filter out far-red light must be developed. Although a plastic material with far-red removing properties is not commercially available at present, several plastic and pigment manufacturers have shown interest in developing such material. The Clemson University and Ohio State University light research teams are currently collaborating with Mitsui Chemicals, Inc., Tokyo, Japan to develop photo-selective greenhouse plastic films or rigid plastic panels. Preliminary results show that certain pigmented films and rigid structural material such as poly-methyl methacylate (PMMA) panels are effective in producing short compact plants similar to chemical growth regulators or liquid $CuSO_4$ filters.

Mitsui Chemicals, Inc. has identified pigments that absorb red (elongation stimulating—tall type) or far-red wavelengths (elongation reducing—dwarf type) from the natural spectrum and are stable in polyethylene films and PMMA panels. Initial trials with dwarf type material were focused on identifying a dye concentration that effectively filters out far-red light from sunlight and reduce plant height while minimizing the PAR reduction (Oi et al., 1998; Rajapakse et al., 1998).

Response of bell pepper (*Capsicum annuum* L.) 'Capistrano', watermelon [*Citrullus lanatus* (Thunb.) Matsum and Nakai] 'Sugar Baby', and chrysanthemum 'Bright Golden Anne' was evaluated in preliminary trials. Far-red intercepting filters reduced height of bell pepper, watermelon, and chrysanthemum plants significantly (Table 4). The height reduction increased as the dye concentration increased but the response varied with the species. In general, watermelon seedlings showed the greatest height reduction followed by bell peppers and chrysanthemums. Although filters with higher dye concentration were more effective in controlling height in some cases, the reduction in transmission of photosynthetic photon flux can reduce the overall quality of plants.

SPECIES AND CULTIVAR RESPONSE TO RED AND FAR-RED INTERCEPTING FILMS. Based on the initial findings, Mitsui has developed both tall (red light interception) and dwarf (far-red light interception) type photoselective films with a dye concentration that result in a 25% light reduction. Light transmission characteristics of tall and dwarf type photoselective films (one tall type and two dwarf type films) are shown in Fig. 2. Tall type film intercepted red wavelengths with maximum interception at 690 nm. Both types of dwarf films effectively intercepted far-red wavelengths with maximum interception at 780 or 730 nm. Unlike $CuSO_4$ filters that removed all radiation above 700 nm, Mitsui films only selectively reduced red or far-red wavelengths from the sunlight.

Table 5 summarizes the response of wide range of plants to tall and dwarf type photoselective greenhouse films. Although plant responses varied with species, most species tested responded well to photoselective filters indicating that photoselective greenhouse covers can be an effective way to control height in a wide range of plants without chemicals.

As the general public becomes more concerned with the chemical use, interest in using nonchemical alternatives to regulate plant growth and to control pests and diseases will increase. With the commercial development of photoselective greenhouse covers or shade material in the near future, nursery and greenhouse industry could reduce costs for growth regulating chemicals, reduce health risks to their workers and consumers, and reduce potential environmental pollution.

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