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Far-Red Light Affects Photosynthate Allocation and Yield of Tomato over Red Mulch

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ABSTRACT

Plastic mulches are frequently used by both large- and small-scale tomato (*Lycopersicon esculentum* Miller) growers to conserve water, control weeds, and keep fruit clean. We hypothesized that changing mulch color to reflect more red light (R) and a higher far-red (FR) to R photon ratio (FR/R) would keep those benefits and improve tomato yield by altering phytochrome-mediated regulation of photosynthate allocation. Photodegradable and nondegradable forms of red plastic mulch were developed to our specifications. Number, size, and total fruit produced over the red plastic mulches were compared with those over standard black plastic. Photodegradable red mulch (placed over a layer of black plastic) increased fruit yield while it was intact, but yield dropped to that of the black control after the red plastic degraded. Nondegradable red plastic resulted in greater yield. Early crop yield advantage of red mulch was evident whether it was placed directly over soil or over a layer of black plastic. We conclude that increased tomato yield over the new red plastic mulch was caused by reflection of FR to the growing plants and its subsequent phytochrome-mediated regulation of photosynthate allocation to developing fruit.

Plastic mulches are widely used to conserve water by blocking rapid evaporation from the soil surface, to control weeds with less herbicides, and to keep soil from splashing onto the fruit in the production of tomato and other food crops (2, 17). Applying water through trickle-irrigation tubes located below the plastic mulch can provide enough water for optimal growth and avoid nutrient leaching by excessive rainfall. The most widely used color of plastic mulch is black (17). We hypothesized that changing mulch color could keep those benefits, while also reflecting a yield-enhancing morphogenic light signal to the growing plants (10).

Plant growth, development, and productivity are dependent on both the quantity and wavelength distribution (color) of light. The quantity and interception of photosynthetically active light have been studied for many years (5, 18, 19), but the role of photomorphogenic light as a regulator of photosynthate allocation in growing plants under field conditions is a recent discovery (7, 14, 15). That is, the color of light received by a growing plant influences how and where the photosynthate is used. For example, R and FR are absorbed by and act through a photoreversible regulatory pigment system, phytochrome. The photon ratio of FR relative to R sets the photoequilibrium between the R-absorbing and FR-absorbing forms of phytochrome (11), which functions as a regulator of photosynthate allocation and adaptive plant development (3, 9, 12, 16). In the field, the amount of FR (and the FR/R ratio) received by a growing plant is influenced by FR reflected from nearby green plants (1, 8, 14, 15). The FR/R received by a growing plant can also be altered by reflection from the soil (or mulch) surface (6, 13). In greenhouse experiments with the same amount of incoming photosynthetic light, more growth occurred in shoots when the FR/R ratio in upwardly reflected light was increased and more growth occurred below ground when the ratio was decreased (6, 10). As cropping systems continue to evolve, the impact of reflected light on yield and quality of plant products needs to be exploited.

Before initiating field experiments, we evaluated morphological responsiveness of tomato and several other food crop species to high vs. low FR/R ratios under controlled environments in which the quantity of photosynthetic light was held constant. Results of an unpublished 1985 test confirmed that photosynthate allocation in tomato was as responsive to phytochrome regulation as was tobacco (*Nicotiana tabacum* L.) (7), another member of the Solonaceae family. Preliminary experiments also showed that R and FR entering from the lower surface of a leaf was as effective as that entering from the upper surface. These combined observations indicated a strong probability that phtosynthate allocation in tomato would be responsive to the FR/R ratio reflected from the soil surface to developing shoots in a field management system in which incoming photosynthetic light was not altered by the colored mulch.

In our first field studies with tomato, yield differed over plastic mulches that were painted with different colors of exterior enamel (4). Subsequently, a large number of field experiments were conducted with a range of paint colors. In most of the experiments, tomato yields were higher over red-painted mulch than over black plastic mulch. However, in some experiments, the yield over red-painted plastic differed between batches of red paint even though they appeared the same to our eyes; i.e., reflection from the different red paints was the same in the visible spectrum (400–700 nm), but the amount of reflected FR (beyond detection with the unaided human eye) and the FR/R ratio received by the growing plants differed. Such inconsistent FR reflection from the different red paints (and plant responses to

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Abbreviations: CRADA, cooperative research and development agreement; FR, far-red light; R, red light.

those differences) emphasized the need to develop the "ideal" reflection spectrum and to formulate a red plastic that would reflect the desired spectrum to the growing plants.

By measuring the reflection spectrum of a sample from each can of paint before using it, we were able to compare growth and productivity of tomato and other crops over a number of slightly different reflection spectra. Based on many experiments, an ideal reflection spectrum was developed for tomato. The working hypothesis for the development of the colored mulch technology was that the reflector should not interfere with incoming light used in photosynthesis, but the photomorphogenic light reflected from the soil (mulch) surface should act in allocation of the photosynthate among plant components, including the developing fruit. This technology has been developed through a USDA ARS cooperative research and development agreement (CRADA) and licensed to Sonoco Products (Hartsville, SC) for manufacture and marketing. The objective of our study was to evaluate tomato fruit yield over photodegradable and nonphotodegradable forms of the new FR-reflecting, red plastic mulch compared with standard black plastic mulch under field conditions.

MATERIALS AND METHODS

Tomato fruit yields over photodegradable and nondegradable red plastic mulch (developed according to our specifications under a CRADA with Sonoco Products Co.) were compared with those over standard black plastic mulch under field conditions near Florence, SC. Plants of the cultivar Celebrity were started and grown to 12 cm in a greenhouse before being transplanted to field plots in the spring of 1994, 1995, and 1996. Soil samples were taken each year and the plots were fertilized according to Clemson University Cooperative Extension Service recommendations for tomato production. The fertilizer was broadcast and disked into the upper 15 cm of soil. Raised beds were formed and black polyethylene mulch (1.5 m wide), trickle-irrigation tubing, and methyl bromide (bromomethane) fumigation were all applied in one operation. The mulch-covered beds were 0.9 m wide and 0.15 m high. They remained undisturbed for at least 2 wk before appropriate colored surfaces were put into place, holes punched, and tomatoes transplanted. The within-row plant spacing was 0.5 m and rows were 2.1 m apart in all experiments. Each year, all branches below the first flower cluster were removed, and the plants were staked according to Clemson University recommendations. Removal of the lower branches (suckers) also resulted in less interference with upward reflection of light from the colored mulch to the developing fruit and nearby leaves. Tomato fruit were harvested on a per plot basis two or three times per week depending on the ripening rate. The fruit were graded according to USDA Agricultural Marketing Service standards and weighed immediately following each harvest. Data were analyzed by analysis of variance (ANOVA) and by least significant difference (LSD) as outlined by SAS Institute (20). Specific details for each of the years are discussed below.

1994

The seedlings were transplanted to field plots on 29 April. There were four rows (replicates), and subplots (mulch colors) were randomized within each row. Each color plot contained 16 plants (the middle 12 were harvested).

The "first generation" of red plastic mulch was photodegradable. It was compared with unpainted black and with a red-painted surface that reflected a spectrum very similar to that used by Decoteau et al. (4). The red plastic was placed on top of the layer of black that was put down prior to fumigation. The black underlayer served two purposes: (i) it blocked transmission of photosynthetic light to the soil surface and (ii) it assured an intact plastic mulch on the soil surface after the red plastic degraded. This photodegradable red plastic began to crack when the earliest tomatoes were about 4 cm in diameter. The degrading red plastic did not change color (i.e., intact pieces continued to reflect the original spectrum); however, cracking continued and most of the red pieces blew away as the first fruit began to ripen, about 1 July. The red plastic was replaced with a fresh layer from the original roll on 15 July. Comparison of yield over the photodegradable red plastic (over the black underlayer) with yields over both red-painted and standard black controls allowed us to evaluate yield-enhancing effects of reflection from the red plastic when the surface changed (i.e., with the red plastic mulch present, absent, and present again) during the season. This approach was essential to determine whether a light signal (primarily the FR/R photon ratio) reflected from the red plastic would be *imprinted* in the seedlings and remain effective for the life of the plants, or whether fruit development would respond to the red mulch only while it was in place.

Because soil temperatures are known to influence horticultural crop production (2), they were measured 10 cm below the various plastic mulches midway between the plants at 0745 h ± 25 min and 1245 h ± 25 min on 7 d without rain from 21 June to 1 July, during early fruit development. Temperatures were taken with a battery-operated, digital display thermometer with accuracy of ± 0.5°C. Twenty separate measurements were taken each time under each mulch (i.e., values presented are means for 140 measurements below each of the three mulches in the morning and 140 near solar noon).

1995

The seedlings were transplanted on 27 April, using the same number of replicates, within-row spacing, between-row spacing, plants per color plot, and plants harvested per color plot as in 1994. The photodegradable red plastic was replaced by one that remained intact for the entire growing season, however. The red plastic was applied in two ways, (i) over a layer of black plastic, and (ii) directly over the weed-free fumigated soil (the black plastic remained in place for 2 wk after the fumigation, but was cut out and replaced by red plastic for this treatment). These two red plastic treatments were compared with black plastic from the same roll used in 1994.

Soil temperatures were measured 10 cm below the various plastic mulches midway between the plants at 0745 h ± 15 min and 1245 h ± 15 min on 12 d without rain from 16 May to 12 June. Ten separate measurements were taken under each mulch at each time with the same thermometer that was used in 1994.

1996

Seedlings were transplanted to field plots on 10 May. There were five rows (replicates) and the color treatments were randomized within each row. Each color plot had 14 plants and the middle 10 were harvested. Red plastic from the same roll used in 1995 was applied over a layer of black plastic and over soil that had some nonsterilized surface soil containing a mixture of viable weed seed sprinkled on it after the original black plastic was removed from the fumigated soil. The black plastic (control) was from the same roll used the previous 2 yr.

Soil temperatures were taken with the same thermometer and depth as described for 1995. Temperatures were recorded in the morning and early afternoon soon after transplant (from 21 May to 5 June) and during early fruit set (from 24 June to 2 July). Soil temperatures were also measured in early afternoon of 6 August, the day before final harvest.

RESULTS AND DISCUSSION

Photodegradable Red Plastic Mulch

Fruit yield over the photodegradable red plastic differed relative to those over black or red-painted plastic (controls) as the 1994 season progressed (Tables 1A, 1B, and 1C). In the first two pickings (combined), yields of both large and total marketable fruit over the red plastic mulch were greater than those over the black and about the same as those over the red-painted mulch (Table 1A). However, the red plastic photodegraded as the first tomatoes were ripening, leaving the plants growing over the intact black underlayer after the second picking (on 1 July). The yield advantage over the photodegradable red plastic diminished rapidly compared with yield over the red-painted control. For example, as shown in Table 1B, yield of large fruit from Pickings 4 and 5 (12 and 15 July) over the degraded red plastic did not differ from the black control and both were lower than those over the red-painted control. Clearly, exposing the seedlings to reflection from the red plastic before it degraded did not imprint a permanent yield-enhancement in the plants.

After the fifth picking, the degraded red plastic was replaced by fresh red plastic from the original roll and fruit development responded accordingly (Table 1C). About 6 wk after the fresh red plastic was placed over the existing black underlayer, fruit yields from Pickings 14 and 15 (combined) on 23 and 26 August over the red plastic were again greater than those over the black control; i.e., yield of fruit that developed over the fresh red plastic responded to conditions associated with the intact red plastic (Table 1C), as did yield during the early season (Table 1A) before it degraded and left the plants growing over the black underlayer. The field test with the photodegradable red plastic demonstrated that red plastic could enhance yield, and that the red surface needed to remain intact not only during early plant growth and early fruit set but during the entire production season.

Soil temperatures measured from 21 June to 1 July (as the early fruit was developing) 10 cm below the black plastic, intact pieces of red plastic (over the black underlayer), and red-painted plastic mulches averaged 25.5, 25.3, and 25.2°C, respectively, in the morning and 29.8, 29.5, and 29.4, respectively, near solar noon. These data suggest that differences in soil temperature (<0.5°C) below the three mulches during this period were minor and contributed little to fruit yield compared with the contribution from reflected photomorphogenic light and its affect on allocation of photosynthate to developing fruit.

Table 1. Fruit yield per 12-plant plot over the first generation of red plastic (photodegradable) vs. black and red-painted plastic mulches at different times during the 1994 growing season near Florence, SC.

Mulch	Large fruit	Total marketable fruit
	kg	kg
A. Pickings 1 and 2, fruit developed before red plastic degraded		
Black (control)	1.9 b†	2.0 b
Red plastic (over black)	3.8 a	3.8 a
Red-painted (control)	3.7 a	3.7 a
LSD (0.05)	1.7	1.6
B. Pickings 4 and 5, fruit developed after red plastic degraded		
Black (control)	17.2 b	17.7 b
Red plastic (over black)	17.2 b	17.4 b
Red-painted (control)	20.6 a	20.7 a
LSD (0.1)	3.1	2.9
C. Pickings 14 and 15, fruit developed after red plastic was replaced		
Black (control)	5.5 b	6.3 b
Red plastic (over black)	8.7 a	9.8 a
Red-painted (control)	8.2 ab	8.8 ab
LSD (0.1)	3.1	3.1

† Values are means per 12-plant plot. Those in the same subcolumn followed by the same letter do not differ significantly at the $P = (0.1)$ level.

Nondegradable Red Plastic Mulch

1995

Number and weight of large fruit and total marketable fruit were significantly greater ($P = 0.01$) over the new red plastic than over the black (control) during the first 2 wk of harvest in 1995 (Table 2A). Early crop yields over the two red plastic treatments did not differ from each other whether the red plastic was placed over a layer of black plastic, which blocked transmitted light from the soil surface, or placed directly over the weed-free soil. The percentages of total fruit that were graded as large were 86, 95, and 93% for tomatoes grown over black, red (with black underlayer), and red (on bare soil), respectively, during this period; and average weights per fruit were about 228, 245, and 243 g for total marketable fruit grown over black, red (with black

Table 2. Large and total marketable fruit yields per 12-plant plot over nondegradable red plastic (over a layer of black plastic, or over weed-free soil) vs. black plastic mulches during the 1995 season near Florence, SC.

Mulch	Large fruit		Total marketable fruit	
	no.	kg	no.	kg
A. Early season, 3 July to 17 July				
Black (control)	78 b†	19.1 b	90 b	20.5 b
Red (over black)	102 a	25.6 a	107 a	26.2 a
Red (over soil)	104 a	26.3 a	112 a	27.2 a
LSD (0.01)	9	3.4	14	2.9
B. All pickings to 28 July				
Black (control)	218 b	49.2 b	257 b	53.3 b
Red (over black)	253 a	58.2 a	285 a	61.4 a
Red (over soil)	241 a	56.9 a	268 ab	59.8 a
LSD (0.05)	15	2.6	19	2.5

† Values are means per 12-plant plot. Those in the same subcolumn followed by the same letter do not differ significantly at the $P = 0.05$ level.

underlayer), and red (on bare soil), respectively, for the early crop. Cumulative weight of large and total fruit harvested during the 25-d season were also greater over both red treatments than over the black mulch (Table 2B).

Early season (16 May to 12 June) mean soil temperatures 10 cm below the three mulches were 24.4, 24.2, and 24.3°C for black plastic, red (with black underlayer), and red (on bare soil), respectively, in the morning and 31.4, 31.2, and 32.0°C in early afternoon. The similarities among soil temperatures below the red (with black underlayer) and the black (control) in 1995 were consistent with findings in 1994 (before the red plastic photodegraded). Thus, the early crop yield differences over red (with black underlayer) vs. black (control) are primarily attributed to spectral composition of light reflected from the red mulch and its affect on allocation of photosynthate to developing fruit. Although yields did not differ significantly between the two red mulch treatments during the 25-d period, the slightly higher midday temperature below the red plastic when placed directly over bare soil (vs. over a layer of black plastic) suggests a possible need for further study of soil temperatures below different colors of mulch during a longer season.

Examinations of the early season larger fruit (developed over red mulch) vs. smaller fruit (developed over black mulch) indicated that both contained the same percentage of dry matter. Thus, the yield advantage over red vs. black mulch was the result of more total dry matter per fruit developed over the red mulch. This is consistent with our hypothesis that the light signal reflected from the red mulch should result in allocation of more photosynthate to developing fruit.

1996

As in 1995, yields of early crop tomatoes were greater over both of the red treatments than over the black mulch (Table 3A). Number and weight of tomatoes over red were also higher than those over black for the entire season (Table 3B). A difference between the red (over soil) treatment in 1995 and 1996 was that there was some herbaceous weed growth below the red plastic in 1996. The possible influence of plant growth under the red plastic was studied because many small-scale growers and suburban gardeners cannot fumigate their soil before growing mulched tomatoes. It was evident that the presence of some plant growth below the red plastic [see "red (over soil)" in Table 3] did not adversely affect tomato yield over the red vs. black mulch. Yield over the red (over soil) mulch treatment unexpectedly increased relative to the other two treatments between 31 July and 7 August during the hot summer days. Possible explanations are (i) plants growing below the red plastic may have raised it sufficiently that rain kept the reflecting surface cleaner and more effective than the red (over black) treatment, and/or (ii) plant growth below the red plastic may have shaded the soil surface enough to have a moderating effect on soil temperature as the final harvest of fruit was developing in late July and early August.

Early season (21 May to 5 June) soil temperatures 10 cm below the black, red (with black underlayer), and red (on soil with some plant growth) were 23.3, 23.2, and 23.1°C, respectively, in the morning and 30.7, 30.1, and 30.9 at noon. Morning temperatures were similar (26.3, 26.2, and 26.1°C) and noon temperatures (31.4, 30.6, and 29.9°C) were slightly lower below the red (on soil) from 24 June to 2 July. Midday temperatures (31.8, 31.0, and 29.3°C) were about 2.5°C cooler 10 cm below the red (on soil) than below the black (control) on 6 August, the day before final harvest. Effects of plant growth below the red plastic needs further study. An important point for growers is that tomato yields were significantly higher over the FR-reflecting, red plastic than over the widely used black plastic mulch, and a small amount of plant growth below the red plastic did not negate yield-boosting effects of the red plastic mulch.

Table 3. Tomato yields per 10-plant plot over the nondegradable red plastic (over a layer of black plastic, or over soil) vs. black plastic mulch during the 1996 season near Florence, SC.

Mulch	Large fruit		Total marketable fruit	
	no.	kg	no.	kg
	A. Pickings 1–4, 22 July to 30 July			
Black (control)	122 a†	31.9 b	127 a	32.5 b
Red (over black)	134 a	35.9 a	137 a	36.2 a
Red (over soil)	132 a	37.3 a	136 a	37.7 a
LSD (0.05)	14	3.4	15	3.6
LSD (0.1)	11	2.7	12	2.9
	B. All pickings through 7 August			
Black (control)	142 b	36.2 b	153 b	37.4 b
Red (over black)	164 a	42.5 a	171 ab	43.1 a
Red (over soil)	169 a	45.8 a	175 a	46.5 a
LSD (0.05)	21	5.0	20	5.1
LSD (0.1)	17	4.0	17	4.2

† Values are means per 10-plant plot. Those in the same subcolumn followed by the same letter do not differ significantly at the $P = 0.05$ level.

CONCLUSIONS

The FR-reflecting, red mulch made to our specifications enhanced early crop yields of tomato compared with yields over standard black plastic mulch. Effectiveness of the red mulch is attributed primarily to the FR/R photon ratio reflected to the developing fruit and nearby leaves from the mulch surface. This allows field plants to receive incoming sunlight for photosynthesis, and morphogenic light reflected from the mulch surface to regulate allocation of photosynthate. Action of the FR/R ratio is through the phytochrome system within the growing plants and it regulates photosynthate allocation to the developing parts, including fruit. The red mulch surface area must remain intact and be large enough to reflect morphogenic light to the developing parts of the plant, especially the fruit and nearby leaves. Also, the reflecting surface must be clean because dust and spray residue that change the mulch surface color alter its reflection spectrum. Yield responses to the red plastic mulch were very similar whether it was placed directly over soil or over a light barrier. The 1996 experiment showed that some plant growth below the red plastic did not result in the loss of yield advantage compared with yield over the black plastic control.

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