An Investigation of Reflective Mulches for Use Over Capillary Mat Systems for Winter-time Greenhouse Strawberry Production

G. E. Meyer, E. T. Paparozzi, E. A.Walter-Shea, E. E. Blankenship, S. A. Adams

Abstract. *Photosynthethically active radiation (PAR) is a principle environmental variable used by horticultural specialists, agronomists, and ecosystem modelers to characterize the quantity and quality of light conducive to plant growth and development. Spatial distribution of PAR in a greenhouse can be quite variable and diffuse throughout the daytime photoperiod, especially at low sun angles in northern regions of the United States. Four colors of reflective plastic mulches (white, red, olive, and black) were evaluated for winter-time strawberry (*Fragaria × ananassa *Duch.) production based on their reflectance and transmittance properties in a double-polyethylene, plastic-glazed Quonset greenhouse in Nebraska. The spectral properties of the plastic film mulches were investigated in the laboratory using a spectral radiometer and integrating sphere. For greenhouse spectral studies, a modified field of view set of LiCOR ™ PAR sensors and infrared thermocouple sensors (IRT/c) were mounted over the greenhouse gravel floor and the strips of plastic films of four different colors. Both incident and reflected PAR and plastic mulch temperatures were recorded during the day using a wireless, LabVIEW ™-based data logger system. The red mulch reflected less than half the amount of PAR than that from the white mulch and the olive and black mulches reflected even less. The white 6-mil reflective mulch was then selected to cover a capillary mat (CapMatII ™) irrigation system in a greenhouse strawberry production study. A three-month production study using the white reflective mulch under 312 strawberry pots resulted in the production of over 1700 saleable berries with a mass of over 19 kg. Plastic mulches could enhance the PAR environment of greenhouses and thus translate to more consistent plant production during winter months.*

Keywords. *Greenhouses, Photosynthetically Active Radiation, Reflective mulches, Capillary mats, Strawberry production.*

Nebraska – the heartland of America – is known nationally and internationally for its agricultural field crop production activities during spring, summer, and fall. However, Nebraska also receives excellent average incident levels of solar radiation of 12 to18 MJ/m^2 (1000 to 1600 Btu/ft^2) per day during the winter months (Bodman et al., 1989). These insolation values are in agreement with solar horizontal radiation calculations for the months of November through March for Nebraska latitudes (ASHRAE, 1985). However, there is in general, a lack of definitive published solar data for the high plains for actual greenhouse fruit and vegetable production during the winter months.

An important question then arises for growing plants in greenhouses: is there adequate light available during the winter months for successful flower and fruit production? Incoming solar energy in greenhouses is partitioned between diffuse (major component on cloudy days) and direct beam (primary component on clear days). Incident direct beam radiation depends on the changing solar altitude and azimuth angles of the sun during the day. Radiant energy incident on greenhouse plants is received from the incoming solar radiation (sky direct and diffuse) and indirectly received from radiation reflected off physical surfaces within the vicinity of the plants. Incident solar radiation available for plant growth is reduced by the optical transmittance of the greenhouse glazing as well as shading due to structural elements and overhead equipment, but may retain some directionality, making some parts of the greenhouse bench brighter than others. The estimated amount of incident light useful for plant growth is reported as Photosynthetically Active Radiation (PAR) photon flux density (PPFD, μmoles m^{-2} s^{-1}). The actual amount of short wave energy intercepted by plants is also related to canopy architecture and plant population. Ideally, a plant fully bathed in PAR (top and bottom leaves) will be a productive plant as long as all other needs are met.

The light environment within a greenhouse includes PAR that is reflected and transmitted from all interior surfaces. Only a few literature reports have presented the use of reflective materials on greenhouse benches to increase the amount of light reflected to plants (e.g., Tarara, 2000). These materials are commonly called reflective mulches. They have been used to reduce weed populations and evaporative loss from soils, while improving the nearby light environment to plants. Researchers have reported a 10% to

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35% increase in canopy lighting using reflective mulches under various plants. Bauerle (1982) reported a slight increase in production when using 4-mil thick, white polyethylene over straw mulch in greenhouse tomato plants. Decoteau et al. (1989) studied reflective mulch surface colors for fresh market tomatoes and found that red mulches increased the early market productivity while producing less foliage. White and silver-colored mulches produced more foliage, but had a lower, early market yield. Their results indicated that surface mulches may affect the microclimate (spectral quality and quantity of light and the soil temperature). Tarara and Ham (1999) showed that reflective mulches were also impermeable to water movement and significantly reduced evaporation from wet soil surfaces.

Black and red reflective mulches tended to increase soil surface temperature, while white reflective mulches resulted in cooler soil surface temperatures. Moreno et al. (2009) observed a 6°C increase in average soil temperatures using black polyethylene. Csizinszky et al. (1995) studied the effect of six reflective mulch colors: blue, orange, red, aluminum, yellow, and white (fall) or black (spring) on fruit yields and on insect vectors of 'Sunny' tomato *(Lycopersicon esculentum* Mill.). They found reduced numbers of whiteflies with orange and aluminum mulches, delayed virus symptom development, and increased yields. Csizinszky et al. (1995) also conducted a spectral study with reflective mulches. Aluminum had the highest short wave reflectance, while black mulches had a lower reflectance. Gough (2001) studied the effect of reflective mulch color on the root architecture of 'Sweet Banana' pepper [*Capsicum annuum* L. (Grossum Group)]. The number of lateral roots produced increased under silver mulch. Smaller numbers of roots were found under clear and black mulches, while the fewest roots occurred under red reflective mulch. Colored mulches influenced the total number of adventitious and lateral roots, but not necessarily the root system architecture of pepper plants. Tarara (2000) provided a table of potential plant responses to mulches under field conditions, including those using black and clear plastic mulches for strawberries. Based on the literature summary provided by Tarara (2000), black plastic mulch would be considered the overwhelming mulch choice for field crops.

Greer and Dole (2003) found that yields of various vegetables were increased when grown using aluminum foil or aluminum-painted reflective mulch. The work of Kasperbauer (2000) suggested that red reflective mulch reflected a higher far-red to red (FR/R) photon ratio that might regulate photosynthate allocation, resulting in an increase in strawberry yields. The difficulty with many studies has been the inability to discern whether the mulch affected the amount of PAR back-reflected into the canopy, whether soil temperatures were affected, or both. Some studies also suggested that brightness rather than color would be more effective. Black plastics utilized as mulches have been shown to affect the amount of heat stored within the covered soil. Clear plastics, on the other hand, would allow PAR to penetrate to the soil surface, but perhaps promote undesirable weed growth under the plastic. Color may also affect the attraction of insects such as white flies. An increased amount of vegetative plant growth or increased leaf-area-index (LAI) would intercept more light energy directly, but may not allow light penetration to the mulch below the canopy. As a result of increased PAR and stored heat, a winter-grown crop might be more profitable.

Takeda (2000), and Takeda and Hokanson (2003) described basic principles and concerns for out-of-season strawberry production in greenhouses. Among these included the design of soilless structures and the development of new cultivars that will fruit under shorter photoperiods. Freeman and Gnayem (2004) outlined principles for cultivating strawberries in greenhouses with mulches using drip irrigation. Reflective mulches were recommended for increasing the PAR environment and also conserving water through vapor barriers. A number of proposed growing systems included hydroponics and hanging bed-pack containers, using an average plant density of 22 plants per m^2 (Paranjpe and Cantiffe, 2004). Plant spacing also influences the development of runner tips for production of plug plants. Strawberries need bench space for berries, runners, and branch crowns.

Capillary mat (CapMat II™, Phytotronics, Inc, Earth City, Mo.) bench fertigation systems could provide an excellent environment for strawberry greenhouse production. Pots would be set directly on the saturated absorbent fabric (Schuch and Kelly, 2006). A difference in water potential drives water from the mat to the pot/mix/plant. As the roots grow to the bottom of the pot, they extract moisture available from contact between the rooting medium and the moist mat. A particular advantage of this method is that leaf surfaces are kept dry, and thus plants are potentially less susceptible to disease and pests. By covering the CapMat with plastic mulch, water loss by evaporation would be reduced, if not eliminated.

Therefore, a major question arises as to how plants in pots using a CapMat system can be integrated with plastic mulch. When pots are set on the mat, they can not be moved nor watered from above, in order to preserve the capillary bond of water. Little or no information is currently available on the use of CapMat systems for strawberry production. Since bench space is also needed for runners, stolons, and berry harvesting, it makes sense to improve the PAR environment with plastic mulch while at the same time reducing evaporation water loss. The hypothesis that was entertained in this article was whether there was increased PAR available by placing plastic mulches over a CapMat system for strawberry production in a greenhouse.

The objectives of this study were (a) to determine the photo reflective properties of four common reflective mulches, (b) to estimate the potential amount of available reflected PAR and changes in mulch surface temperatures that might enhance the production of greenhouse strawberries using a CapMat system.

Materials and Methods

A plastic mulch PAR study was conducted during late November and December 2009. The study was conducted within a 7.2- × 29-m (22- × 90-ft) double polyethylene, commercial-style production Quonset greenhouse oriented north-south, located on the East Campus of the University of Nebraska (40.8°N, 96.7°W; 358-m elevation). The greenhouse was fully instrumented to monitor inside and outside temperature, humidity, inside photosynthetically active radiation (PAR) amounts, heat energy used, ventilation, and water/fertilizer utilization events. Mulches over a time clock–controlled, CapMat system were later used in a strawberry production study that is only briefly mentioned here.

Plastic Films Tested

Four colored polyethylene films: red, black, dark olive samples each 0.1 mm (1 mil) thick and two white samples at 0.4 and 0.6 mm (4 and 6 mil) thick, respectively, were used (Ken-Bar Manufacturing, Peabody, Mass.). Mulch strips were cut 2 m (6 ft) wide and placed across the width of the greenhouse floor. The three 2 m (6 ft) wide strips of polyethylene film alternated with a 2 m (6 ft) width of exposed gravel (the base floor of the greenhouse) are shown in figure 1. Each film was left in place for 7 to 14 days during which reflected PAR and surface temperature measurements were acquired before rotating to the next colored mulch. Aluminum films were not used or considered since this film would be in constant contact with moisture from a CapMat™ irrigation system, resulting in corrosion and leaching of the metal into the irrigation water. Aluminum would also represent a higher film cost. Therefore, aluminum films were considered impractical for winter strawberry production.

Greenhouse PAR Sensor Studies

Modified PAR sensors (LiCor 190SA Quantum sensors, Lincoln, Nebr.) were suspended over the polyethylene mulch strips and exposed gravel sections to measure reflected PAR (μmoles m^{-2} s^{-1}). Each quantum sensor was mounted facing downward over the mulch or gravel using a short polyvinyl chloride (PVC) pipe collar to restrict the amount of reflected energy received to a one m^2 of target area (figs. 2 and 3). A standard Li-COR quantum sensor measures radiation hemispherically, necessitating the use of a view restrictor for the sensor measuring the radiation reflected from the surface below the sensor. The amount of top-down incident PAR available was measured using upward facing Li-COR quantum sensors with full hemispherical exposure (fig. 3). A reflectance coefficient was calculated as the ratio of restricted field of view reflected PAR to the available incident PAR, given as:

$$\text{Reflectance coeffiecient (\%)} = \left[\frac{\sum_i^n \frac{PAR_{\text{Reflected}}}{n}}{\sum_i^n \frac{PAR_{\text{Incident}}}{n}} \right] \cdot 100\% \quad (1)$$

where n is the extent or number of logged data points recorded during the photoperiod. For each day, the reflectance coefficients measurements were separated into three convenient, but relatively similar time periods: morning (20 values from 9 A.M. to 10:30 A.M.), noon (20 values from noon to 1:30 P.M.), and afternoon (20 values from 2:00 P.M. to 3:30 P.M., CST) for three consecutive days of measurement for each mulch film and corresponding gravel treatments. In addition, the total solar radiation was measured with Li-COR pyranometers (LiCor LI-191SA), both under the glazing and outside the greenhouse (10-min averages and expressed in μmoles m^{-2} s^{-1}). Greenhouse air temperatures (°C) and relative humidity (%) were measured using LabJack 1050 and U12 data loggers (LabJack, Inc, Denver, Colo.). Greenhouse floor gravel and mulch temperatures were measured using infrared thermocouples (OS36SM IRT/c, Omega Engineering, Stamford, Conn.) installed next to the quantum sensors. The corresponding average differences between the surfaces temperatures and ambient air temperature were also computed. Sensors were calibrated as noted by signed certificates by the manufacturers.

Figure 1. Reflective mulch and surface temperature study with (a) 6-mil white plastic and (b) 1-mil red plastic (Rotation of black and dark olive plastic mulches are not shown).

WLS-TEMP wireless 24-bit data loggers (Measurement and Computing, Inc, Norton, Mass.) were used with the radiation and temperature sensors. A dedicated Windows XP computer with a transmitter/receiver and located in an air-conditioned cabinet recorded the data to an Excel file format. Software for the acquisition system was implemented using LabVIEW 8.2® (National Instruments, Austin, Tex.). The greenhouse computer was connected to the campus internet system so that the entire system could be readily accessed or monitored remotely from office or home.

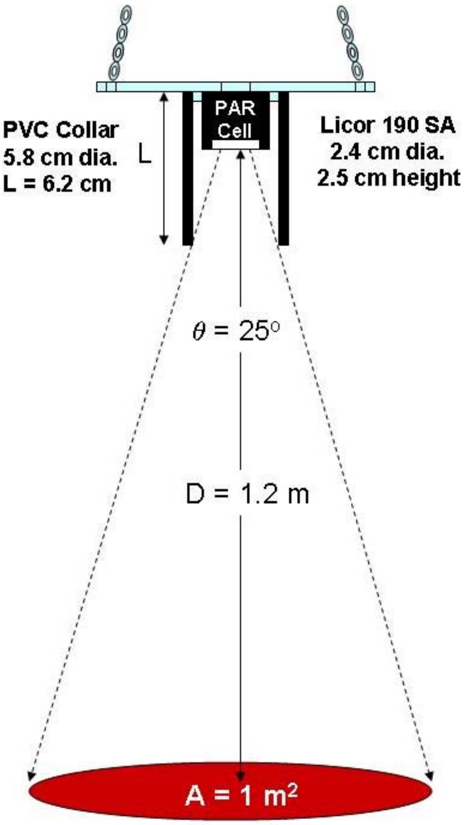

Figure 2. Special PVC collar over downward facing PAR cell restricted reflected radiation to 1 m^2 of the reflective mulch or gravel surface.

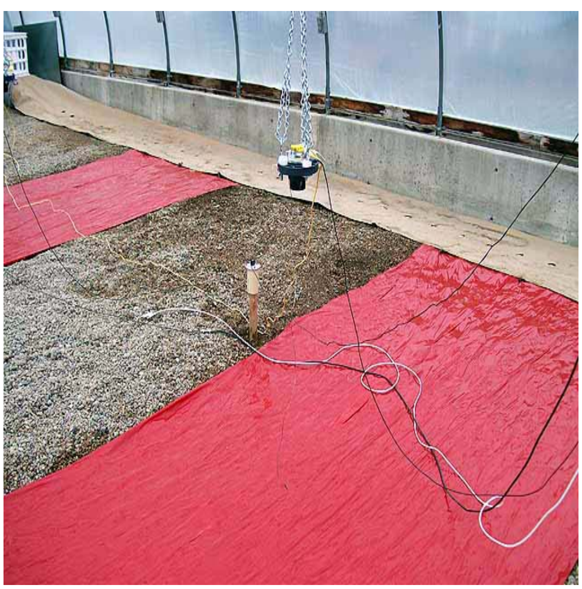

Figure 3. View of Li-COR PAR sensors and infrared temperature sensor: one incident and one reflective PAR over red plastic reflective mulch.

Integrating Sphere Experiments

Five small but representative samples of each polyethylene film used in the greenhouse study were individually placed in a Li-COR integrating sphere port illuminated with a halogen light source (peak about 800 nanometers). The integrating sphere was mounted with a Spectron SE-590 Spectroradiometer (Denver, Colo.). The light reflected from, and transmitted through, the mulch samples was analyzed. Light was conserved with an internal barium sulfate reference plug, used as a reference to the light incident available to the sample. The Spectron instrument used a diffraction-grading device which measures radiance from 400- to 1100-nm wavelengths (λ), but conserves all light energy within a barium sulfate, interior painted sphere. All reflectance and transmittance calculations included an adjustment for stray light. Reflectances and transmittances at each wavelength were calculated as:

Reflectance (%) =
[Reflected(λ) – stray(λ)/Reference(λ) – stray(λ)] 100% (2)

Transmittance (%) =
[Transmitted(λ)/Reference(λ) – stray(λ)] 100% (3)

The concept of the integrating sphere is to conserve and direct all light components to comply as best as possible with the Kirchhoff energy law. It was expected that the Spectron measurements would achieve higher reflectance or transmission coefficient values than those calculated from measured LiCor PAR data in the greenhouse. However, the relative trends for the Spectron measurements were expected to compare with or complement the LiCor greenhouse (PAR) measurements.

Experimental Design and Analysis

A simple block design of three single-colored mulch strips and corresponding exposed gravel was run as a separate experiment for 7 to 14 days before rotating to the next mulch experiment. Replications (blocks) were not different from each other so the data were pooled across blocks. From these measurements, the average, maximum, and minimum over each time period were calculated. The experiment was treated as a split-plot with the mulch/gravel treatment as the whole plot factor and time period as the split-plot factor. Using PROC GLIMMIX (SAS Institute Inc., Cary, N.C.), average, maximum, and minimum values for mulch and gravel were compared for each time period for three consecutive days of each experiment. Statistical differences between reflectance coefficients for the mulch and gravel treatments were estimated using least square means (alpha=0.05).

The studies were conducted with plastic films right off the roll. Later, holes for 6-in. pots would need to be cut through the film so that the plant roots could access moisture provided by the CapMat. A special hole cutting board for the mulch was devised. The jig was designed to provide a sufficient spacing distance between the pots, resulting in 6 plants per m^2. This spacing would provide adequate room for strawberry stolons to develop and extend to receive light. The extra space also allowed for manual berry harvesting and visual inspection of the plants. Consequently, the additional contribution of reflected PAR from the mulch would be important for productivity. Productivity was determined by the number and fresh weight of strawberries produced.

Results and Discussion

Photosynthetically active radiation (PAR) utilized by healthy green plants is based on peak absorption [which is equal to 100% – (reflectance + transmittance)] in the blue (~400 nm) and red (650-750 nm) by chlorophyll, with considerable reflectance at 550 nm (Gates et al., 1965). Thus, plastics used as mulches need to reflect largely in the blue and red wavelengths to enhance the photosynthetic activity of plants. To verify this, an integrating sphere and spectroradiometer were used.

Integrating Sphere

Figures 4 and 5 show the results of the average reflectance and transmittance values of the mulches obtained using the Spectron SE 590 spectroradiometer and Li-COR integrating sphere assembly. The use of the integrating sphere therefore provided the maximum theoretical reflectance and transmittance of a mulch film. As shown in these figures, white mulches tended to favor the visible wavelengths, especially in the blue when reflecting light. Reflectance also varied from 80% to 85% from blue to near-infrared, respectively. Transmittance values were only 20% to 40% across the range of wavelengths measured. There appeared to be a slight difference in the reflectance and transmittance values relative to the thickness of the white plastic mulch. The thicker white plastic mulch appeared to reflect more and transmit less radiant energy than the thinner white plastic mulch so that there was no discernable difference in absorption.

Of the remaining mulches, the red reflective mulches provided the greatest amount of reflected energy in the red and near infrared spectral regions, but less than half of that of the white mulches and very little across the shorter wavelengths. In addition, the red mulch also transmits considerably more red and near-infrared energy than the white mulch film (as much as 64% compared to 13% to 40%).

The olive and black reflective mulch films reflected the least amount of energy (4% to 24%). The olive plastic film

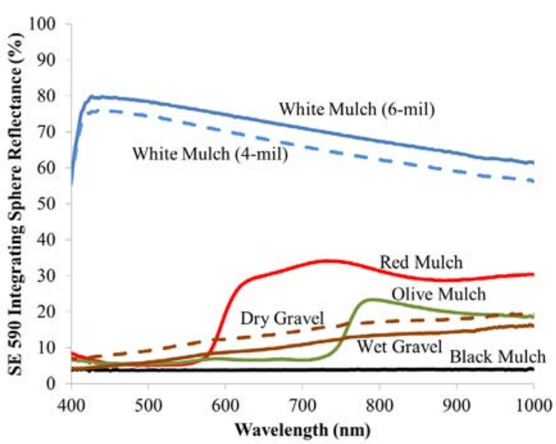

Figure 4. Integrating sphere analysis of reflectance of plastic mulch samples, and wet and dry gravel.

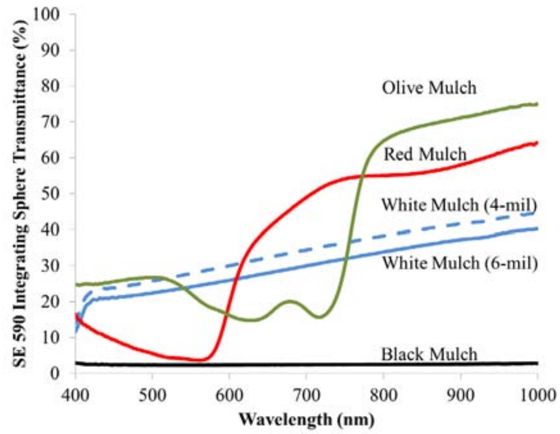

Figure 5. Integrating sphere analysis of the transmittance of the plastic mulch samples.

had the highest transmittance in near-infrared (45% to 75%). The mulches with lower reflectance and higher transmittances might perform in a similar manner to clear plasticmulches by allowing shorter wavelengths to reach the underlying surface, perhaps trapping the longer wavelengths. However, this phenomenon has yet to be confirmed.

Greenhouse Mulch Reflectance

Figures 6a and 7a show the amounts of reflected PAR for 6-mil white mulch and 1-mil red mulch, respectively, which occurred during three to six consecutive days. The unit of time on these plots is hours, derived from the LabVIEW program. As expected, mulch reflectance coefficients were found to be smaller than those values obtained with the integrating sphere, but with similar trends (data not shown).

Figures 6b and 7b show the diurnal surface temperature profiles for the white and red mulch strips, respectively, along with gravel temperature. There appeared to be a trend for higher surface temperatures with the reflective mulch strips when compared to the exposed gravel. These mulches tended to trap heat in the air beneath them during the day and condense vapor from the trapped air at night. Condensation would reduce air and surface temperatures under the mulch as a result of the latent heat phase change. The frequency of the nighttime cycling of the natural gas heating system control may also affect latent heat and moisture entrapment. Condensation on mulch surfaces and greenhouse glazing has been observed as early morning ‘rain’ in some commercial Nebraska greenhouses that do not apply ventilation to remove the latent heat in order to reduce heating costs.

The differences between average, maximum, and minimum reflection coefficient values for the mulch films when compared to the exposed gravel for the three time periods are shown in figure 8. White mulch measurements gave reflectance coefficients from 10.5% to 16.0% (5% to 15% more than exposed gravel), compared to 1.7% to 2.4% for red, olive, and black (0 to 8.0% less than exposed gravel), respectively. The statistical results and comparisons are discussed in the next section.

Statistical Results for the Greenhouse

White 6-mil mulch resulted in consistently significantly higher reflectance coefficients than exposed gravel in terms

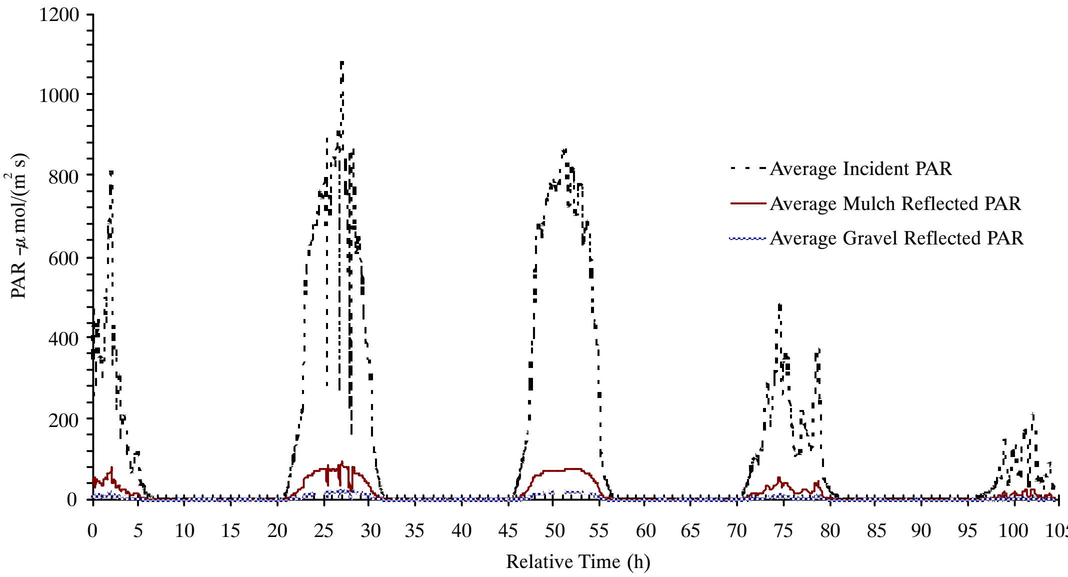

Figure 6a. Greenhouse incident and reflected photon fluxes for individual strips of a 6-mil white plastic mulch.

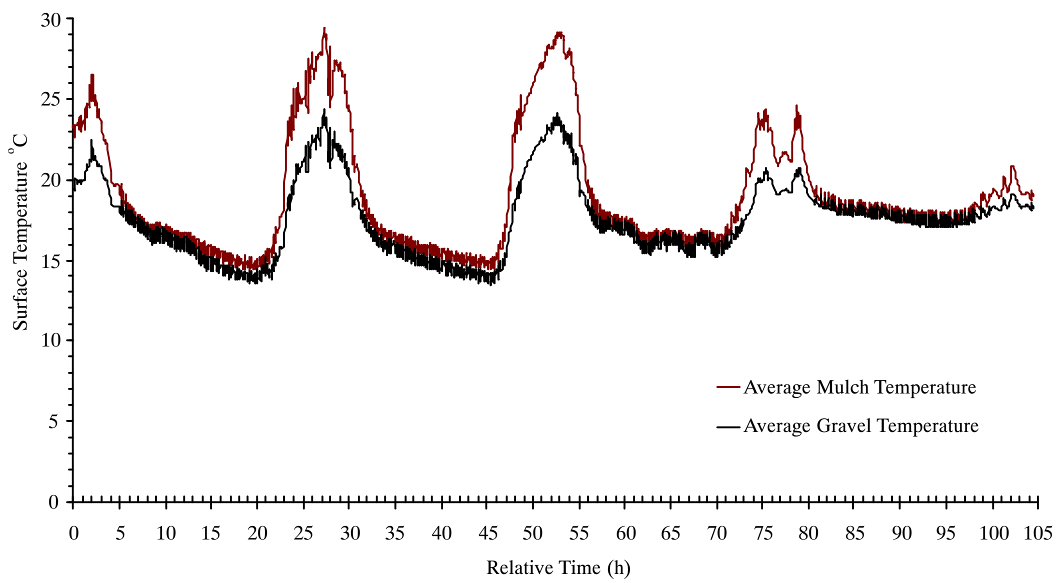

Figure 6b. Surface temperatures of individual strips of 6-mil white plastic mulch and bare gravel.

of the average, maximum, minimum values during all three daily testing periods (morning, solar noon, and afternoon). White 4-mil mulch showed no significant differences between the mulch and gravel during the morning tests. However, white 4-mil mulch yielded significantly higher reflectance values than gravel during the noon and afternoon testing periods. With the white 4-mil mulch film, there were no significant differences at $P > 0.05$ between mulch and gravel for maximum reflectance values during all three daily periods. However, there were statistical differences at $P > 0.08$. The discrepancy is attributed to the high variability in the data coupled with the low number of degrees of freedom. White 4-mil mulch always yielded statistically higher minimum reflectance values than the gravel.

In contrast, reflectance coefficients for exposed gravel were significantly higher than the red, olive, and black mulches for the three experimental days but not consistently across all three time periods. There was no significant difference in minimum reflectance coefficients between the red mulch and gravel for any of the time periods. There was no significant difference in minimum reflectance coefficients between the olive mulch and gravel during the morning and afternoon time periods, while there was a significant difference during the noon period. There was no significant difference between the black plastic mulch and exposed gravel maximum reflectance coefficients during the morning and noon time periods. Consequently, the white mulches provided the best reflected PAR for a greenhouse environment in the northern latitudes during winter and were therefore selected for the greenhouse winter strawberry production study.

Production Considerations

A follow-up cultivar trial of greenhouse potted strawberries was undertaken from January through March 2010, using the most reflective of the films tested over a

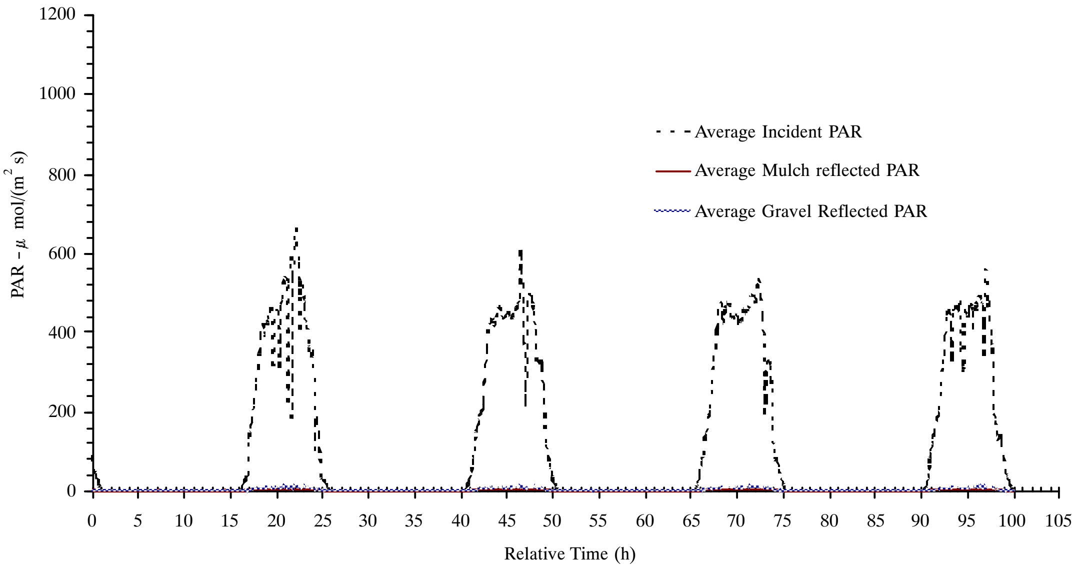

Figure 7a. Greenhouse incident and reflected photon fluxes for individual strips of 1-mil red plastic mulch film.

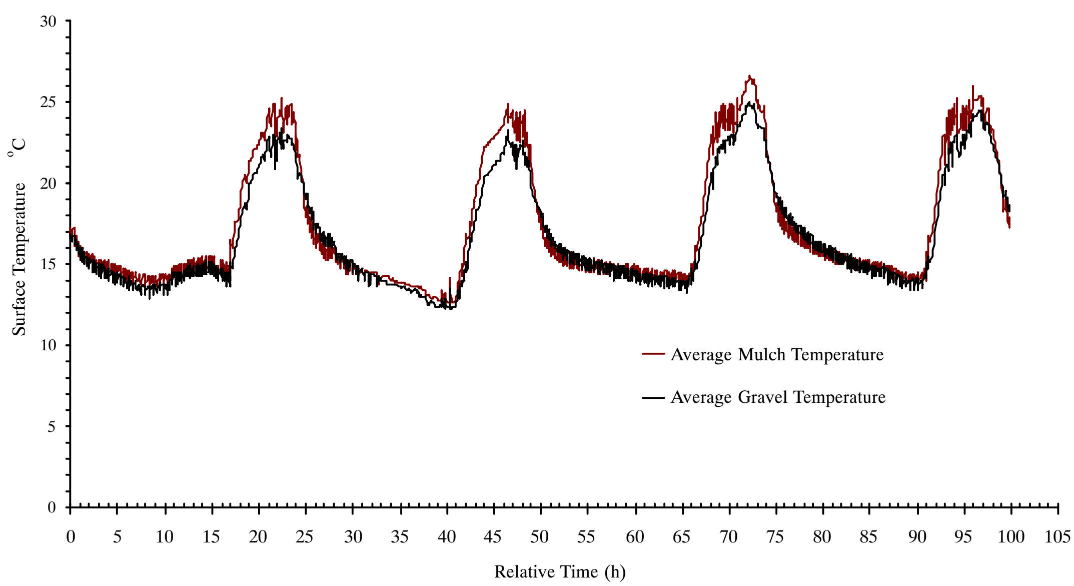

Figure 7b. Surface temperatures of individual strips of 1-mil red plastic mulch film and bare gravel.

CapMat fertigation system. The white polyethylene 6-mil mulch was selected to enhance the light environment for the greenhouse strawberry plants and to serve as a covering for the CapMat watering system. A greenhouse arrangement using the white mulch with the CapMat for an actual production study is shown in figures 9 and 10.

Potential condensate accumulation below the films, when placed directly on the floor, was noted. There was also an issue of algae accumulation on the CapMats which will need to be addressed. The thickness of the 6-mil white mulch and the subsequent lower transmittance was thought to be sufficient to discourage algae growth; however, algae did grow under the mats during the first greenhouse production study. Algae can also provide a surface for fungus gnats. A possible solution is the white top/black bottom bi-layer reflective film. However, a cost analysis in using the two mulches must be considered, as the cost of the bi-layer is usually higher but could be off-set if an algae-free CapMat could be reused.

During the following 2010, 3-month study, 24 pots of 13 different cultivars of strawberries produced a total of over 1700 saleable berries (19 kg) with this system. The cultivars Honeoye, Evie-2, and Strawberry Festival produced the most berries (Paparozzi et al., 2010). Additional production studies are currently underway. Preliminary indications showed that plants grown on the white reflective mulch using the system tend to flower in late October and produce marketable berries between mid-November and the beginning of December (optimal marketing time) and then peak again in March.

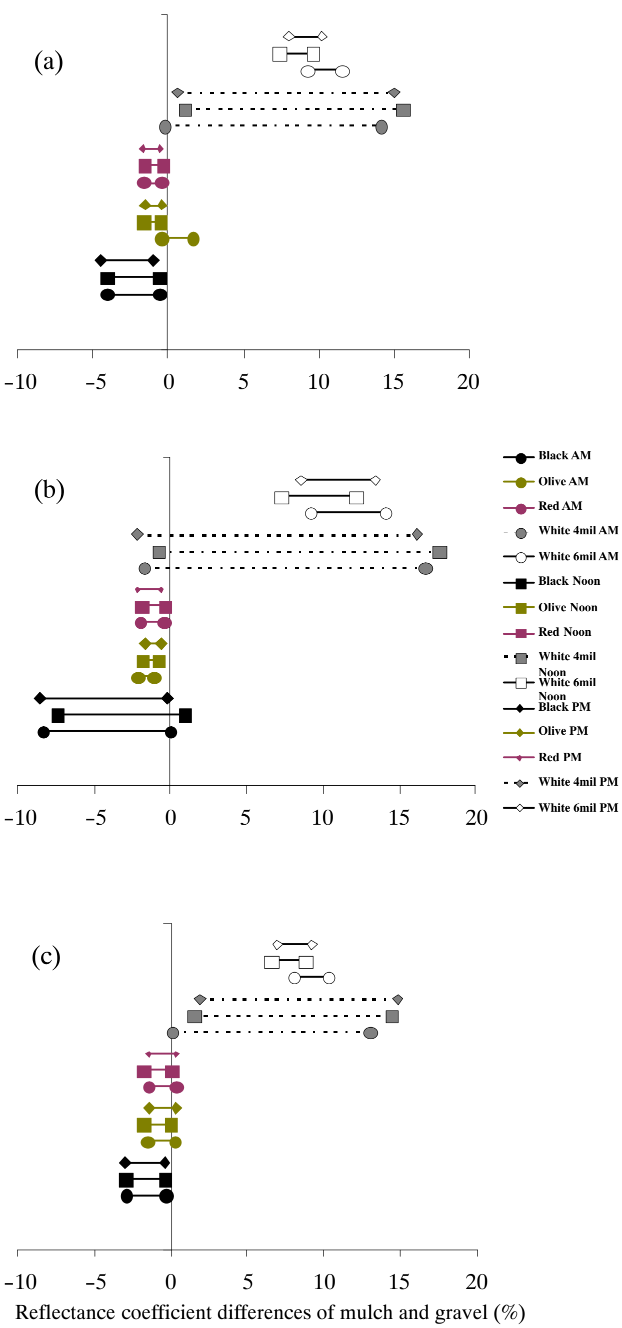

Figure 8. Ranges of computed differences: (a) average values, (b) maximum values, and (c) minimum values between mulch and gravel coefficient values, from mulch and gravel reflectance measurements during the morning (AM), noon, and afternoon (PM) for black, olive, red, white 4-mil, or white 6-mil mulches during the greenhouse study.

Conclusions and Suggestions for Future Research

The literature shows some benefits of plastic reflective mulches that include the reduction of evaporative loss, alteration of surface temperatures, insect population control, and alteration of the light environment. Our investigation indicated that combining highly reflective plastic mulch in a greenhouse environment with a CapMat system did provide favorable conditions for growing strawberries during the winter months in the Midwest; the result is attributed to an enhanced PAR light environment. The light environment likely could have been enhanced further with the use of other reflective materials such as vertical reflectors, especially for low solar angles during the winter. However, introducing

Figure 9. Initial setup of a capillary mat fertigation system showing just the lower vapor barrier (black), capillary mat, and black emitters. The reflective mulch with holes for the pots was placed over the capillary mat fabric and emitters.

Figure 10. Greenhouse production in operation (a) capillary mat with white reflective plastic mulch on top (b) close-up of strawberry plot spacing (30.5 cm between rows and 51 cm within the rows) over the plastic.

such reflectors should not impede grower and worker access to the plants. A future study should include crop production comparisons with such vertical reflectors.

Acknowledgements

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