Aluminum Foil, Aluminium-painted, Plastic, and Degradable Mulches Increase Yields and Decrease Insect-vectored Viral Diseases of Vegetables

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SUMMARY. For decades, vegetable growers have used black polyethylene mulch to warm the soil in early spring, reduce weeds, and conserve soil moisture. Use of plastic mulch can increase crop yields and improve fruit quality. This article reviews research performed with plastic, aluminum foil, aluminum-painted, and degradable mulches. Most research focused on the effects of plastic mulches on insects and viruses they vector, and on yields. Aluminum foil and aluminum-painted mulches are effective at repelling insect pests, especially aphids (Aphididae) and thrips (Thripidae). Yields are often higher with black plastic compared to bare ground. Clear plastic is rarely used in the U.S. because it can encourage weed growth, unless a herbicide or fumigant is used underneath. Colored mulches can increase yields and control pests, but color may be less important than brightness of the mulch or contrast with bare soil. New forms of photodegradable mulches eliminate the need to remove and dispose of plastic at the end of the growing season, but have not been widely adapted because they tend to degrade prematurely.

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Organic mulches, such as hay and straw, have been used for many years to conserve water and control weeds, but they also keep soil cooler, which can delay early season growth. During the last century, manufactured materials such as paper, aluminum foil, and plastic have been used as mulches. Each has advantages and disadvantages when compared to bare-soil culture, and compared to each other. Since mulches are used for a wide range of crops in a range of geographic areas with different natural rainfall and temperature conditions, one should expect some variability in yield responses. Our objectives in preparing this review article were to 1) describe the effects of plastic mulches, focusing on yield, insect pest populations and virus incidences and 2) to compare degradable mulches to nondegradable forms.

Aluminum foil and aluminum-painted mulches

As early as the 1950s, researchers began experimenting with aluminum foil as a mulch. A 3-year study at Pennsylvania State University tested aluminum foil mulch on numerous crops (Pearson et al., 1959). Aluminum foil mulch always increased yields when compared with bare soil, but the increase was more noticeable in years with less-than-adequate rainfall, presumably due to water conservation. In 1955, marketable total season tomato (*Lycopersicon esculentum*) grown on aluminum mulch yielded 264 lb (119.8 kg) more (63%) per 24 × 30-ft (7.3 × 9.1-m) plot than on unmulched plots; in 1956, yields were 78 lb (35.4 kg) higher (20%); and in 1957, they were 102 lb (46.3 kg) higher (32%). Increased yields also occurred in sweet corn (*Zea mays*) by an average of 25% over the 3-year study, peppers (*Capsicum annuum*) by 50%, lima beans (*Phaseolus limensis*) by 19%, carrots (*Daucus carota*) by 25%, cucumbers (*Cucumis sativus*) by 66%, and lettuce (*Latuca sativa*) by 15% (Pearson et al., 1959). In two 1968 studies, aluminum foil mulches repelled green peach aphids (*Myzus persicae*) (Adlerz and Everett, 1968; Wolfenbarger and Moore, 1968).

Significant problems existed with aluminum foil. It was hard to lay, expensive, and sometimes caused physical damage to the plants that came in contact with it (Pearson et al., 1959). Reflective aluminum plastic mulches were developed and became the focus of new research.

Before a discussion of aluminum mulches can begin, it is necessary to define aluminum. Of the 28 studies cited in this paper in which aluminum mulch was used, eleven studies used black plastic that had been painted with aluminum-colored paint, three used white-on-black plastic that was painted on the white side with aluminum-colored paint, one used white plastic painted with aluminum-colored paint, two used black-on-white plastic with the black side painted with aluminum-colored paint, five were described simply as silver, and three used aluminum, with no other description given. The remaining treatments are described as aluminum backing over home insulation, silver mulch applied over clear plastic, silver embossed polyester, silver embossed polyethylene, silver-brown co-extruded, silver embossed polyethylene netting applied over soil, silver embossed polyethylene netting suspended on hoops, silver Styrofoam latex spray mulch, aluminum painted onto translucent brown latex spray mulch, metallized foil-like aluminum on white, and aluminum painted-like matrix on black. Since 19 of the aluminum mulch treatments were painted onto plastic mulch, the term aluminum-painted will be used throughout this paper to describe plastic mulches exhibiting reflective properties.

Yields of numerous vegetable species increased when grown on aluminum foil or aluminum-painted plastic mulch (Table 1). More research has been done with tomatoes and squash (*Cucurbita* spp.) than other crops, and almost all studies have shown significant increases in yields of both species (Table 1). Other vegetables that have shown yield increases on aluminum-painted mulch include eggplant (*Solanum melongena*), peppers, and potatoes (*Solanum tuberosum*) (Black and Rolston, 1972; Lamont et al., 1999; Mahmoudpour and Stapleton, 1997).

Not all studies have shown significant increases in yields, however. In three Florida studies, no yield increases occurred in zucchini, peppers, and tomatoes grown on aluminum-painted mulch (Kring and Schuster, 1992; Powell and Stoffella, 1990, 1993). Although Kring and Schuster (1992) reported no significant yield

Table 1. Significant effects of tested mulches (crop and locations given) on crop yields, insects, and viruses.

Aluminum foil, black plastic. Summer squash (*Cucurbita pepo* var. *melopepo*), Florida (Moore et al., 1965).
Aphids (Aphididae) reduced 50% to 70% on aluminum foil. Leaf miner (*Liriomyza* spp.) numbers were also reduced.
Virus symptoms delayed by 2 or more weeks on aluminum foil.

Yellow, pink, green, red, black, white, orange, light blue, and dark blue plastic, and aluminum foil. Sugar beets (*Beta vulgaris*), cucumber (*Cucumis sativus*), and lettuce (*Latuca sativa*), Wisconsin (Jones and Chapman, 1968).
Aphids were most attracted to yellow, followed by pink, green, red, and black. They were least attracted by white, orange, light and dark blue, and aluminum foil.
Aluminum foil reduced beet mosaic virus symptoms by 72%, black by 45%, yellow by 27%, and white by 18%. Aluminum foil and yellow reduced cucumber mosaic virus symptoms by 70% to 77%, black by 54%, and white by 37%.

Aluminum foil, black plastic. Bell peppers (*Capsicum annuum*) and tabasco peppers (*Capsicum frutescens*), Louisiana (Black and Rolston, 1972).
Yield of bell pepper grown on aluminum foil were increased 45% over no mulch and 36% over black plastic.
Aphids reduced on aluminum foil.
Virus symptoms on tabasco peppers on aluminum reduced by 57%.

Clear, blue, and black plastic. Cucumbers, Hungary (Basky, 1984).
Clear mulch reduced virus symptoms 70%, blue mulch reduced virus symptoms by 77%.

Black plastic painted with aluminum paint. Yellow squash, Louisiana (Lancaster et al., 1987).
Marketable yield of mulched plants was 457 bushels (15,438.0 kg) versus 241 bushels (4,256.4 kg) of unmulched plants.
Virus symptoms were significantly delayed on aluminum-painted mulched fields.

Aluminized, aluminum over black plastic, and black plastic. Fall tomatoes (*Lycopersicon esculentum*), South Carolina (Schalk and Robbins, 1987).
Highest yields were obtained on black plastic.
Aluminum mulches repelled aphids, but tomato pinworm (*Keiferia lycopersicella*) and tomato fruitworm (*Heliothis zea*) damage increased.

Black, white, and aluminum-painted black plastic. Tomatoes, Alabama (Brown et al., 1988).
Greatest yields were produced on aluminum-painted.
Black and white attracted aphids. Aluminum-painted had no effect on aphids.

Aluminum-painted and black plastic. Tomatoes, Arkansas (Scott et al., 1989).
Aluminum-painted reduced thrips (Thripidae). Black had no effect on thrips. Not studied

Black plastic painted white, silver, red, and black. Tomatoes, South Carolina (Decoteau et al., 1989).
Greatest early yields were produced on red. Dark mulches (red and black) had higher yields than light (white and silver) ones.

Black, white, and aluminum-painted black plastic. Tomatoes, Alabama (Brown et al., 1989).
Highest yields were produced on aluminum-painted.
White and black increased thrips. Aluminum-painted mulch had no effect on thrips numbers.

White, aluminum backing from home insulation, and aluminum-painted black plastic. Yellow squash, Oklahoma (Conway et al., 1989).
Reflective aluminum increased yield.
Reflective aluminum delayed virus symptom onset longest.

In 1984, used Styrofoam (Dow Chemical Co., Midland, Mich.) insulation panels painted red, white, or black. In 1987 and 1988, used straw erosion control blankets painted red, white, or black. Cowpeas (*Vigna unguiculata*), South Carolina (Hunt et al., 1990).
Red mulch provided significantly higher yields.

Aluminum-painted black plastic and black plastic. Tobacco (*Nicotiana tabacum*), pepper, and tomato, Louisiana (Greenough et al., 1990).
Aluminum-painted mulch reduced western flower thrips (*Frankliniella occidentalis*) numbers by 68% in tomatoes and 60% in peppers. Thrips numbers reduced 33% in combined planting of tobacco, pepper, and tomato.
Tomato spotted wilt virus (TSWV) symptoms reduced by 64% in tomato with aluminum-painted mulch and 78% in pepper with aluminum-painted mulch. TSWV symptoms reduced 60% in combined planting of tobacco, pepper, and tomato.

Aluminum-painted black plastic and black plastic. Zucchini and tomatoes, Florida (Powell and Stoffella, 1990).
Aluminum-painted mulch did not increase yields in tomato or squash.
Aluminum-painted mulch had no effect on sweetpotato whiteflies (*Bemisia tabaci*) in squash.

White-on-black plastic painted aluminum, yellow, black, white, black with yellow edge, or black with silver edge. Yellow squash, Alabama (Henshaw et al., 1991).
Aluminum-painted mulch had highest yields. Yellow, black with silver edges, and black with yellow edges also improved yields over bare ground.
Aphids significantly reduced on aluminum-painted mulch. Other colors were not as effective, but they were better than bare ground.
Aluminum-painted mulch delayed mosaic virus symptoms by about 14 d.

Black plastic, black plastic painted white, black plastic painted with white paint mixed with ground mica, black plastic painted with aluminum paint, white plastic, aluminum laminated plastic film. Pepper and tomato, Florida (Kring and Schuster, 1992).
Mulches had no effects on yields.
Aluminum-painted mulch was about the same as aluminum mulch and superior to black plastic and bare soil in repelling aphids. It was also effective in repelling thrips, but results were inconsistent. Numbers of leafminers and spider mites (*Tetranychus urticae*) were not affected by aluminum-painted mulch.
Fewer plants infected with aphid-transmitted viruses on aluminum mulches.

Straw mulch painted white, red, pale blue, 2-inch (5.1 cm) stripes of blue, 2-inch stripes of orange, and unpainted. Potatoes (*Solanum tuberosum*), South Carolina (Matheny et al., 1992).
White, pale blue, and striped mulches produced >15% more marketable tubers than unmulched plants.

Table 1 (continued). Significant effects of tested mulches (crop and locations given) on crop yields, insects, and viruses.

Black-on-white plastic painted silver, white, yellow, black, or black with yellow edge. Yellow squash, Alabama (Brown et al., 1993).
Aluminum-painted mulch produced significantly higher marketable yields than other colors.
Aluminum-painted mulch significantly reduced aphid populations; other colors reduced aphid numbers but not as much as aluminum.
Aluminum-painted mulch reduced cucumber mosaic, watermelon mosaic I and II, zucchini yellow mosaic, and squash mosaic virus symptoms by 10-13 d.

Aluminum-painted black plastic in spring, aluminum-painted white plastic in fall, and black plastic. Zucchini and tomatoes, Florida (Powell and Stoffella, 1993).
Zucchini and tomato yields not affected by aluminum-painted mulch.
Sweetpotato whitefly numbers were not affected by aluminum-painted mulch.

White-on-black plastic mulch painted blue, orange, red, aluminum, yellow, or white for fall studies; spring studies used black plastic painted the same colors. Tomatoes, Florida (Csizinszky et al., 1995).
In spring, red and aluminum-painted increased early and extra-large fruit yields. Early and overall yields were lowest on blue. In fall, yellow, blue, and red had lowest yields; white had highest.
Aphids were least numerous on aluminum-painted and yellow and most numerous on blue. Aluminum-painted had the fewest thrips and blue the most thrips. Yellow, aluminum-painted, and orange had the fewest whiteflies. Red attracted whiteflies.
Orange and aluminum-painted delayed virus symptoms.

White plastic overlaid with photodegradable black mulch, white plastic, black plastic, and black plastic painted white after 2, 20, 40, 60, or 80 d. Tomatoes, squash, South Carolina (Graham et al., 1995).
Yields on all mulches were not significantly different.

Silver embossed polyethylene, white embossed polyethylene, silver-brown co-extruded polyethylene, silver embossed polyethylene netting on soil, silver embossed polyethylene netting on hoops, silver-pigmented Styrofan synthetic latex spray mulch (BASF Corp., Charlotte, N.C.), white Styrofan synthetic latex spray mulch, silver embossed polyester. Zucchini, California (Summers et al., 1995).
Yields were 70% to 80% higher on silver spray and silver polyethylene mulches.
Aphid numbers were lowest on silver spray and silver polyethylene mulches.
Silver spray and silver polyethylene mulches delayed virus symptoms by 7 to10 d.

Black, silver, white, yellow, and black with yellow edge plastic. Yellow squash, Alabama (Brown and Boyhan, 1996).
Yields on aluminum were significantly higher than those on bare ground.
Aluminum mulch delayed mosaic virus symptoms.

Black-on-white plastic mulch painted yellow or aluminum, white plastic. Yellow squash, Alabama (Brown et al., 1996).
Marketable yields on aluminum-painted and white were significantly higher than yields from bare soil or black plastic.
Aluminum-painted significantly reduced aphid populations over black plastic and bare soil.
Aluminum-painted mulch delayed virus symptoms by as much as 3 weeks. White and yellow also delayed virus symptoms.

White-on-black and black plastic. Tomatoes, Louisiana (Hanna et al., 1997).
Marketable and total yields were significantly higher on white mulch.

White-on-black plastic painted orange, yellow, aluminum, white, or black in fall; black plastic painted same colors in spring; yellow plastic with 93% soybean oil emulsion (Stoller Chemical Co., Houston, Texas) applied to plants twice during the season, orange with Saf-T-Side mineral oil (Brandt Consolidated, Pleasant Plains, Ill.) applied weekly. Tomatoes, Florida (Csizinszky et al., 1997).
Yields of extra-large tomatoes were highest on yellow + oil. Marketable yields were highest on aluminum and yellow + oil.
Silverleaf whiteflies (*Bemisia argentifolii*) preferred white in fall and black in spring.
Orange + oil, yellow + oil, and aluminum-painted were slower to show virus symptoms.

Black, white, red, blue, yellow, and aluminum paints applied over biodegradable translucent brown mulch base latex spray mulch. Eggplant (*Solanum melongena*), California (Mahmoudpour and Stapleton, 1997).
Aluminum-painted produced significantly higher numbers of fruit (44% to 221%), and total fruit weight was higher (42% to 237%), than other colors.

Black embossed, high-density black, green, infrared transmittable, selective low thermic, and silver on brown plastic, kenaf fiber, newspaper pellets, newspaper hydromulch. Muskmelons (*Cucumis melo*), Texas (Brandenberger and Wiedenfeld, 1997).
Total yields were higher on all plastics compared to bare ground, but there were no differences between plastics.

Photodegradable red placed over black plastic, photodegradable red alone, red-painted plastic, black plastic. Tomatoes, South Carolina (Kasperbauer and Hunt, 1998).
Nondegradable red resulted in highest yields. Early yields were excellent on red mulches. Photodegradable red mulch increased fruit yield while it remained intact.

Red, yellow, blue, silver, and black plastic. Greenhouse tomatoes, Pennsylvania (Orzolek, 1999).
10.7% higher yields were produced on blue, aluminum and yellow. Yield on red was 3.5% higher than black.
Highest numbers of thrips were on blue. Yellow was the first color to attract greenhouse whitefly (*Trialeurodes vaporariorum*) and potato aphids (*Macrosiphum euphorbiae*); thrips were also high on yellow. Red, aluminum, and black had low levels of all pests.

Black plastic in spring, white-on-black plastic in fall, metallized foil-like aluminum on white plastic, metallized aluminum on white plastic with center black strip, aluminum painted-like matrix on black plastic, aluminum on black plastic with center black strip, aluminum matrix on white with white or black strip down center. Tomatoes, Florida (Csizinszky et al., 1999).
Metallized aluminum, aluminum-painted, and white had similar yields in fall. In spring, yields and fruit size were greater on aluminum-painted.
Silverleaf whitefly numbers on metallized aluminum were lower than on aluminum-painted.
Tomato mottle virus symptoms were lower on metallized aluminum mulch in fall but not in spring.

Table 1 (continued).

Black, aluminum-coated plastic with a silver reflective appearance, silver over clear plastic, and black with two aluminum-coated strips. Cucumber and squash, Virginia (Caldwell and Clarke, 1999).
In cucumber, there were six times as many striped cucumber beetles (*Acalymma vittata*) and spotted cucumber beetles (*Diabrotica undecimpunctata howardi*) on black plastic as on aluminum, and almost three times as many beetles on striped black and aluminum. In squash, there were 5 times as many beetles on black plastic and 2.5 times as many on striped plastic as there were on aluminum.
Black, red, white, silver, green, yellow, clear, blue. Tomatoes, Tennessee (Coffey et al., 1999).
In 1997, red mulch produced the highest early yields. White mulch had significantly lower yields than all others did. Black and silver produced highest yields overall. In 1998, no significant differences occurred.
Red and black plastic. Tomatoes, New Hampshire (Loy et al., 1999).
Yields on red mulch were 3% to 20% higher than on black mulch.
Red, black, infrared transmitting IRT-100 (AEP Industries, South Hackensack, N.J.) and silver plastic. Tomatoes, Iowa (Taber et al., 1999).
Early yields were higher on red and IRT-100. Total yields were highest on silver and red.
Silver, red, and black plastic. Potatoes, Pennsylvania (Lamont et al., 1999).
Silver mulch provided highest yields.
Red and black plastic. Strawberries (*Fragaria ×ananassa*), South Carolina (Kasperbauer, 2000).
Red mulch increased yield 10% to 20%.
Clear, black, and infrared transmitting IRT–76 (AEP Industries, South Hackensack, N.J.) plastic. Pepper, corn (*Zea mays*), and muskmelon, Saskatchewan, Canada (Waterer, 2000).
Clear mulch produced the highest yields.

increase, the weight of marketable tomatoes grown with aluminum-painted plastic mulch was more than four times the weight of tomatoes grown with black mulch [52.0 lb (23.59 kg) versus 11.8 lb (5.35 kg), respectively]. In one of the studies conducted by Powell and Stoffella (1990), the authors stated that sweetpotato whitefly (*Bemisia tabaci*) numbers were very low in all plots. Higher pest densities may have resulted in more damage and lower overall yields on control plots.

In most studies, aluminum-painted mulches repelled aphids and thrips (Table 1). Aluminum-painted plastic mulch reflects light in the B (400 to 500 nm) and near-ultraviolet (395 nm) regions of the spectrum (Csizinszky et al., 1999). Kring (1972) postulated that aluminum mulches may repel aphids by reflecting skylight, or aphids may be responding to the contrasting radiation from the soil and nearby plants. Aluminum foil and aluminum-painted plastic mulches reflect more radiation towards the abaxial sides of leaves, but they emit less longwave radiation because they are usually cooler than light-absorbing mulches (Ham et al., 1991). However, this increase in radiation may increase leaf temperature and water use (Aase et al., 1968; Ham et al., 1991). Shortwave light repels aphids (Kring, 1972), and Ham et al. (1991) theorized that the shortwave reflectance of a mulch has a greater impact on the leaf environment than does mulch surface temperature.

Silverleaf whitefly (*Bemisia argentifolii*) and greenhouse whitefly (*Trialeurodes vaporariorum*) numbers were also reduced in three studies (Csizinszky et al., 1995, 1997; Orzolek, 1999), but sweetpotato whiteflies were unaffected in two studies in Florida (Powell and Stoffella, 1990, 1993). The differences in efficacy may be partly explained by pest management practices. In the earlier studies conducted by Csizinszky et al. (1995, 1997), researchers used *Bacillus thuringiensis* and methomyl for insect control, and Orzolek (1999) used the biological control agents *Encarsia formosa* and *Aphidius colemani* in a greenhouse study, while Powell and Stoffella (1990) used endosulfan in a field study.

Aluminum foil laminated on paper mulch reduced the number of turnip aphids (*Lipathis erysimi*) in cabbage (*Brassica oleraceae* var *capitata*) in Tennessee but did not reduce the number of convergent lady beetles (*Hippodamia convergens*) (Corsoro et al., 1980). In Florida, Moore et al. (1965) found more honeybees (*Apis mellifera*) in the aluminum foil plots than in black plastic or bare soil. Schalk and Robbins (1987) found that, although aphid numbers were lower in fall tomato plots covered with aluminum-painted mulch than in plots covered with black plastic, tomato pinworm (*Keiferia lycopersicella*) and tomato fruitworm (*Heliothis zea*) numbers increased. In a 1965 study, leaf miner (no species given) numbers were lower on aluminum foil than on black plastic (Moore et al., 1965), as were striped (*Acalymma vittata*) and spotted cucumber beetles (*Diabrotica undecimpunctata howardi*) in a 1999 study (Caldwell and Clarke, 1999).

When aluminum-painted mulches repel the vector insects, transmission of the mosaic viruses vectored by insects is also reduced; such viruses include cucumber mosaic virus, papaya ringspot virus, watermelon mosaic virus II, zucchini yellows mosaic virus, squash mosaic virus, tomato spotted wilt virus, and tomato mottle virus (Table 1). Several studies have shown that aluminum-painted mulch delays virus symptoms on squash by as much as 7 to 21 d (Table 1). Significant reductions in virus incidences also have been recorded on tomatoes, peppers, sugar beets (*Beta vulgaris*), and cucumbers (Table 1). Young plants are particularly susceptible to virus infection (Broadbent, 1964; Zitter, 1977), and a reduction of insect vectors early in the season decreases virus incidence. As virus pressure increases, the beneficial effects from aluminum-painted mulches also increase. According to Summers et al. (1995), "The level of virus infection at first harvest is a better indicator of mulch effectiveness than the (insect) counts themselves."

In most studies, aluminum-painted mulches have shown beneficial effects. The question is, Do we see increased yields because of reduced pest populations or because of reduced viruses that are vectored by these insects? Comparisons between studies are difficult to make for numerous reasons. As has already been mentioned, aluminum plastic mulches are referred to in the literature by several names, including aluminum, reflective, silver, and aluminum-painted. All of these mulches are capable of transmitting, absorbing, and reflecting solar radiation at different wavelengths. In a study conducted by Ham et al. (1993), the researchers showed that reflective mulch and silver reflective mulch had very different optical properties. In another study, metallized, foil-like aluminum mulch reduced silverleaf whitefly numbers more than aluminum-painted mulch (Csizinszky et al., 1999), but Conway et al. (1989) found that both mulches provided similar marketable yield increases and disease symptom delay.

Colored plastic mulches

Recent studies have shown that colored plastic mulches can affect the light quality received by a crop, thus altering plant growth morphology (Fortnum et al., 1995), and can affect populations of insect pests that vector viruses, especially aphids, thrips, and whiteflies (Aleyrodidae) (Table 1).

Black plastic has been tested and used commercially for several decades. Because of its wide availability and low cost, black plastic is used more often than any other plastic mulch (Lamont, 1993). Black plastic warms the soil 4 to 5 °F (2.2 to 2.8 °C), and eliminates most weed problems since light transmission is drastically reduced (Hopen and Oebker, 1976). Several studies have shown increased yields of tomatoes grown on black plastic when compared with bare soil (Schalk and Robbins, 1987) and white plastic mulch (Coffey et al., 1999; Decoteau et al., 1989). Insect numbers are often high on black plastic, however. Aphids were attracted to black plastic in a 1968 study (Jones and Chapman, 1968). Brown et al. (1989) saw increased numbers of thrips on tomatoes, and Csizinszky et al. (1997) noted increased silverleaf whiteflies on tomatoes. In a study conducted by Scott et al. (1989), however, black plastic had no effect on numbers of thrips in tomatoes, and black plastic led to low levels of all pests in a study on greenhouse tomatoes (Orzolek, 1999). Beet mosaic virus incidences were 45% lower on sugar beets and cucumber mosaic virus symptoms were 54% lower on cucumbers on black plastic compared with bare soil (Jones and Chapman, 1968).

Mulches that selectively transmit certain wavelengths of light were the next advancement to become available. The best-known are the infrared transmitting mulches (IRTs) that transmit infrared light but block most photosynthetically active radiation (PAR). The best-known IRTs are AL–OR (brown) (Polyon-Barkai Industries, Tel Aviv, Israel), and IRT–76, IRT–64, and IRT–70 (all blue-green) [AEP Industries, South Hackensack, N.J. (no longer manufactured)]. IRTs increase soil temperatures 6 to 8 °F (3.3 to 4.4 °C) while suppressing weeds, but they are not widely utilized because they cost about 25% more than black plastic (Byczynski, 1995), and they are not as widely available as black plastic.

Other colored mulches are also wavelength selective. They affect the intensity of far red and red light reflected into the crop canopy (Decoteau et al., 1986; Decoteau and Friend, 1991) and may affect insect populations.

While trials featuring aluminum-painted mulches have yielded mostly positive findings on crop production, colored mulches have produced mixed results. According to Mahmoudpour and Stapleton (1997), "The influence of mulch colour on crop growth and productivity has been postulated to be highly specific, and may vary with plant taxa, climate, seasonal conditions, etc." Fortnum et al. (1997) noted that plant response to color is stronger in spring than in fall, and this may be due to PAR, temperature and canopy interactions.

Plants grown on colored mulches may have lower insect pest numbers early in the season. Later, crop foliage covers the mulches, reducing pest suppression capacity (Csizinszky et al., 1995). However, with heavily pruned crops, such as tomatoes, the mulch continues to be effective throughout the season (Kasperbauer and Hunt, 1998; Mahmoudpour and Stapleton, 1997).

Another possible benefit from colored mulches is increased plant height. In a Louisiana study on fall-grown tomatoes, aluminum-painted and white plastic mulches increased plant height compared to tomatoes grown on bare soil (Schalk and Robbins, 1987). A Florida study showed that fall-grown tomatoes were taller with aluminum-painted and yellow mulches than with orange, white, or black plastic (Csizinszky et al., 1997).

WHITE AND WHITE-ON-BLACK MULCH. White mulches keep soil temperatures cooler than other mulches, so they are usually used with summer- and fall-planted crops. One problem with white and white-on-black mulches is that they tend to lose their whiteness quickly; dust and soil accumulate and the mulch may become more yellow. Thus, white and white-on-black mulches may become attractive to pests (see the section on yellow mulch below) (Summers et al., 1995).

The effects of white mulches on yields were inconclusive: tomato yields were increased on white-on-black compared to black in a Louisiana study (Hanna et al., 1997), squash yields were increased on white but not as much as on aluminum-painted in an Alabama study (Brown and Boyhan, 1996), no effect occurred on tomato yields in a 1995 study (Graham et al., 1995), and white produced the lowest tomato yields in a 1999 study (Coffey et al., 1999). Treatment effects seem to be at least partly due to geographic location, since lowest yields were in Tennessee and higher yields occurred further south. Regardless of location, time of year did not have an effect on yields.

In three studies, aphids, thrips, and silverleaf whiteflies were attracted with white (Brown et al., 1988; 1989) and white-on-black mulch (Csizinszky et al., 1997). Aphids were reduced in three other studies (Brown et al., 1993; Henshaw et al., 1991; Jones and Chapman, 1968). Kring (1972) noted that white color may sometimes attract aphids and other times repel them, because white surfaces both transmit and reflect all colors. In an experiment using white-colored insect traps, Childers and Brecht (1996) found that white attracted far more thrips than yellow traps. They showed that white surfaces reflected light in the violet-blue (below 500 nm) range, and this color was highly attractive to thrips.

BLUE MULCH. Yield increases occurred in studies with blue mulch. Matheny et al. (1992) found a 15% increase in potato yields when the plants were grown on blue mulch compared with red mulch, and Orzolek (1999) recorded a 10% increase in greenhouse tomatoes grown on blue mulch compared with black.

In two studies, aphids were repelled by blue mulch (Basky, 1984; Jones and Chapman, 1968), and attracted in two other studies (Corsoro et al., 1980; Csizinszky et al., 1995). Thrips and whiteflies are apparently attracted by blue mulch (Csizinszky et al., 1995; Orzolek, 1999). Other studies have also shown that thrips seem to prefer blue sticky traps (Gillespie and Vernon, 1990; Hoback et al., 1999). Western flower thrips are highly attracted to traps with a spectral reflectance between 400 and 480 nm (Chu et al., 2000).

As with aluminum mulch, the differences in the effect of blue mulch on insects may be explained by the differences in the shades of blue color. Pale blue, azure blue, true blue, sky blue, and dark blue were all terms used in the literature when discussing the colors of blue mulch.

YELLOW MULCH. Three studies using yellow mulch on tomatoes produced varied results. Yellow mulch decreased yields (Csizinszky et al., 1995), but delayed symptom onset of several mosaic viruses (Brown et al., 1996). Greenhouse tomato yields were increased by 10% with yellow mulch (Orzolek, 1999).

Yellow color is an attractant for aphids, thrips, and whiteflies (Jones and Chapman, 1968; Orzolek, 1999). As such, yellow mulch could be part of an integrated pest management strategy, where the mulch is used to attract insects and those plants are then sprayed with an insecticide. Csizinszky et al. (1997) demonstrated this in a study, applying soybean oil twice as an insecticide. Yields from these tomato plants were increased and incidence of tomato mottle virus was decreased.

RED MULCH. Red mulch increased yields of cowpeas (*Vigna unguiculata*) (Hunt et al., 1990) and strawberries (*Fragaria ×ananassa*) (Kasperbauer, 2000). Red mulch also increased early tomato yields, but not overall yields in several studies (Coffey et al., 1999; Csizinszky et al., 1995; Decoteau et al., 1989). Both early and total yields were increased in other studies (Kasperbauer and Hunt, 1998; Taber et al., 1999).

The increase in early fruit yields may be due to increased early flower numbers. Tomato plants grown on red or black mulch produced more flowers earlier than those grown on white mulch (Decoteau et al., 1986). In a California study with eggplant, aluminum-painted and red mulches produced three to five times as many flowers early in the season as compared to the translucent brown plastic mulch control (Mahmoudpour and Stapleton, 1997). The increase in number of early flowers may be due to an increase in far-red light in the plant canopy. Red and black mulches increase the ratio of far-red to red light (Decoteau and Friend, 1991). In far-red light, phytochrome A increases, which promotes flowering (Lin, 2000). Light-colored mulches (white and yellow) increase the amount of red light that the plants receive. Phytochrome B, which is stimulated by red light, inhibits flowering (Lin, 2000).

In at least one Florida study, silverleaf whitefly numbers increased on red mulch compared to aluminum-painted mulch (Csizinszky et al., 1995). Red mulch was also more attractive to aphids than white, aluminum-painted, blue, or orange mulch for several crops (Jones and Chapman, 1968).

CLEAR MULCH. Clear mulches may work well in cold climates. Since clear mulches promote weed growth under them, preplant herbicides or fumigants are often used before laying the mulch. In a Canadian study, yields of pepper, sweet corn, and muskmelon (*Cucumis melo* var. *reticulatus*) were increased on clear mulch (Waterer, 2000). The use of clear mulch on sweet corn grown in Iowa reduced days to maturity by up to 10 d on silty loam soil, but had no effect on maturity on a loamy sand (Aguyoh et al., 1999). In a Hungarian study, aphid numbers were lower on clear mulch than on bare soil (Basky, 1984).

OTHER COLORS. In two Florida studies on tomatoes, orange mulch increased yields and delayed tomato mottle virus symptoms (Csizinszky et al., 1995, 1997). Orange mulch also repelled whiteflies (Csizinszky et al., 1995) and aphids (Jones and Chapman, 1968). Pink mulch attracted aphids, as did green mulch, in a 1968 study (Jones and Chapman, 1968).

FURTHER ASPECTS OF PLASTIC MULCHES. Jones and Chapman (1968) found that mulches need to cover at least 50% of the soil to be effective, and Maelzer (1986) noted that mulches must cover about 60% of the soil surface in the field.

Degradable mulches

Biodegradable plastic mulches have become available in the last few years but have not been widely used because of their high cost (Lawton et al., 1999). Mulches made of a combination of starch and biodegradable plastic cost much less, but may degrade too rapidly. In a 4-year Taiwanese study, for instance, these mulches degraded 33 to 83 d after placement (Yang, 1999).

Another form of degradable mulch is sprayable, synthetic latex film, often called latex spray mulch (LSM). These mulches are biodegradable, water-dispersible sprays that are easier to apply than plastic and can be incorporated into the soil instead of being removed. Therefore, disposal costs are reduced 100% and waste management is eliminated (Mahmoudpour and Stapleton, 1997). LSMs will reduce soil splash and can be oversprayed with any color of oil-based paint, but do not control weeds.

Photodegradable plastic mulches break down under ultraviolet light. These films are more expensive than standard plastic mulch and have not proven completely effective in increasing yields (Swaider et al., 1992). Plastigone (Plastigone Technologies, Ft. Myers, Fla.), for example, is a plastic mulch that has time-released formulations available for short-term or longer-term breakdown. The mulch contains iron and copper compounds that break down after exposure to light. When the mulch degrades, it first cracks into pieces that eventually turn into powder. Further degradation occurs in the soil, where microbes attack the remaining fragments. A concern with this product is that the remains of heavy metals in the soil could build to toxic levels (Ennis, 1987). However, in a 6-year study, no differences were observed in heavy metal (iron, lead, nickel, copper, cadmium, and chromium) content of crops grown in soil containing debris of degradable mulches (Yang, 1999).

Degradation rates are influenced by the crops grown. A photodegradable mulch breaks down more slowly when used under crops that cover more of the mulch (e.g., squash), and more quickly on crops such as tomatoes, that allow more light penetration (Csizinszky et al., 1995; Graham et al., 1995; Scott et al., 1989). Geography also affects breakdown; in regions and seasons that receive less solar radiation, the mulch is slower to degrade.

In an interesting study conducted in South Carolina in the mid-1990s, Graham et al. (1995) placed photodegradable black mulch over nondegradable white mulch, hoping to raise temperatures in spring and lower them in summer. Tomato and squash yields were unaffected by the mulch, but soil temperatures did fall after the white mulch was exposed. Thus, another crop could be planted into the white mulch, without the added expense and inconvenience of laying more mulch. In the same study, a coextruded photodegradable film with a photodegradable black surface over a photodegradable white surface was not very effective, because the black and white surfaces began to degrade almost simultaneously.

A Kansas study tested photodegradable mulch vs. nondegradable mulch on asparagus (*Asparagus officinalis*) (Marr and Lamont, 1990). The hypothesis behind the study was that a degradable mulch would be well suited to the perennial asparagus crop, allowing plant establishment in the first year without interfering with spear production in following years. However, crowns grown for a year under regular black plastic mulch were substantially larger because the nondegradable plastic improved soil water moisture during the hot summer months. Kasperbauer and Hunt (1998) tested a photodegradable and a nondegradable mulch; however, the photodegradable mulch disintegrated too quickly and had to be replaced halfway through the season.

Work on biodegradable plastics containing a corn starch base has been conducted for several years (Swaider et al., 1992). For the most part, starch-based films break down too quickly and unpredictably to be commercially useful.

Paper mulches were used in the first half of the century (Flint, 1928), before synthetic plastics were developed during the 1940s and 1950s. As a general rule, paper mulch degrades too quickly. To make paper mulches last longer, they have been coated with tar, wax, or vegetable oil (Shogren, 2000; Vandenberg and Tiessen, 1972). In a 1995 study, for example, cooking oil was applied to kraft paper mulch, but the oil increased light transmission and allowed weeds to grow under the mulch (Anderson et al., 1995). Shogren (2000) found that kraft paper mulches impregnated with vegetable oil-based resins maintained their integrity for 8 to 12 weeks, but they also transmitted light and allowed weed growth.

A kenaf paper mulch used in a Texas study on muskmelons was unsuitable for commercial production. All of the mulch was torn apart by a thunderstorm early in the first year of the 2-year study (Brandenberger and Wiedenfeld, 1997). In the same study, two forms of newspaper mulch were also used, but neither newspaper pellets nor the newspaper hydromulch improved yields. The authors hypothesized that the organic mulches tied up nitrogen in the soil.

Organic mulches (such as straw) have not been cost-effective in increasing yields or controlling insects and their damage (Brandenberger and Wiedenfeld, 1997). Organic mulches usually cool soil temperatures, rather than warm them (Hill et al., 1982), thus reducing early yields. Organic mulches are also more difficult and costly to lay than plastic films.

Economics

Black plastic mulch is by far the least expensive of the available mulches. The higher prices of other colors of mulch can be justified if they accomplish pest management objectives. For example, the cost of aluminum-colored mulch might be recouped when growing a high-value crop under high thrips or aphid-vectored virus pressure.

Aluminum-painted black plastic mulch is much less expensive than aluminum-colored mulch, even when considering the additional labor and cost of the paint, but is less convenient. According to Kring and Schuster (1992), "The reduced insect infestations and reduced virus incidence could outweigh the added inconvenience and expense of applying aluminum paint."

Other economic considerations exist besides the cost of the mulch. For instance, a delay of virus symptoms for as little as one week may grant a grower a virus-free peak harvest. Labor costs would be reduced because fruits would not have to be graded. After peak harvest, the grower could plow under the crop and replant the field, rather than continuing to harvest small quantities of fruit, which is generally not profitable (Conway et al., 1989).

In Virginia, aluminum-painted mulch eliminated the need for pesticidal control of cucumber beetles (Caldwell and Clarke, 1999). This allowed the crop to be sold as pesticide-free, at a price 25% higher than conventionally-produced fruit, which translated into a $1,200/acre ($2,965/ha) increase in revenue (Caldwell and Clarke, 1999).

Brandenberger and Wiedenfeld (1997) studied strengths and removal times of several plastics and found that the two were related. The stronger the film, the less time it took to remove it at the end of the season, because the plastic was still in one piece rather than many. There were no differences in yield with the plastic mulches, so the authors recommended that "the decision regarding which mulch to use should be based on durability and ease of removal, rather than on differences in how the various mulches affected crop growth" (Brandenberger and Wiedenfeld, 1997).

Conclusions

Most of the studies show aluminum-painted mulch to increase yields, repel insect pests and decrease insect vectored virus incidences. White and yellow mulches often increase pest populations, while red and black mulches often increase early yields. All plastic mulches, except for clear, exclude weeds, while degradable plastic, paper, and organic mulches are less efficient in their ability to exclude weeds or increase yields. Currently, biodegradable mulches are not cost effective, but manufacturers are continuing to find new ways to improve them. However, most of the studies cited attempted to prove only one or two hypotheses. For instance, a study may have examined whitefly numbers and virus symptoms for a single virus, but did not investigate other insects and diseases or plant characteristics such as plant height. Similarly, all the factors that may have contributed to higher yields, insect numbers, or virus symptoms, such as seasonal rainfall, soil fertility, specific spectral properties of the mulches tested, method of mulch application, and insect populations either were not studied or were not reported. Although most of the crops studied were annuals that bear aboveground fruit, the differences between crops, cultivars, and time of year make comparisons difficult. In addition, brightness of the mulch and variability in reflected spectra within each color may contribute to variability in results among studies.

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