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Mulches for Weed Management in Vegetable Production

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1. Introduction

The practice of applying mulches for the production of vegetables is thousands of years old (Lightfoot, 1994; Rowe-Dutton, 1957). Typically mulching involves placing a layer of material on the soil around the crop of interest to modify the growing environment to improve crop productivity. The primary purpose for using mulches is for weed suppression in the crop to be grown. Mulches typically function by blocking light or creating environmental conditions which can prevent germination or suppress weed growth shortly after germination. However, numerous other benefits are often obtained including: increased earliness, moisture conservation, temperature regulation of the root zone and above-ground growing environment, reduced nutrient leaching, altered insect and disease pressures, and, in some instances, reduced soil compaction or improved soil organic matter (Lamont, 2005; Lamont, 1993; Ngouajio and McGiffen, 2004; Rowe-Dutton, 1957). The use of mulches typically results in higher yields and quality in vegetable crops enhancing profitability for the grower.

1.1 History of mulching in vegetable systems

A wide variety of mulches have been utilized throughout history. Lithic-mulches, which include pebbles and gravel as well as volcanic ash, may be some of the earliest documented mulches used in vegetable production. Depending on the site and crop grown, lithic-mulches could take the form of mounds around individual plants, long rows or ridges of larger stones, or vast areas where an entire production site is covered in pebbles or volcanic ash (Lightfoot, 1994). Although primarily used in areas with scarce moisture, lithic-mulches also modulate fluctuations in soil temperatures as well as reduce weeds (Lightfoot, 1994). Some of the earliest documented sites where lithic-mulches were used date to 200 B.C. and are found in the Negev desert of Israel (Kedar, 1957). These mulches may have been used with grapevines or olive trees; though, it is unclear if they were used for vegetable production (Mayerson, 1959 as cited in Lightfoot, 1994). The Maori people of New Zealand used gravel mulches in fields between the years of 1200 and 1800 AD to grow sweetpotatoes [*Ipomoea batatas* (L.) Lam.] and maize (*Zea mays* L.) (Lightfoot, 1994; Rigg and Bruce, 1923). In a practice dating back several hundred years, growers in the Lanzhou area of China have used river pebbles at a depth of 7-10 cm for the production of melons (*Cucumis* sp.)

(Lightfoot, 1994; Rowe-Dutton, 1957). Pieces of slate were also used as mulches under melons in England nearly 200 years ago; however, this was likely a way to keep fruit dry as well as warm the plants rather than for weed control (Williams 1824 as cited in Rowe-Dutton, 1957).

Dust mulching is another practice that persists to this day; although, it is not a true mulching technique since no materials are applied to the soil. Dust mulching is the practice of repeatedly and shallowly cultivating the soil surrounding the crop to create a pulverized (dust) layer of soil (James, 1945). A theory, though proven to be incorrect, is that by creating a finely textured layer of soil at the surface, capillarity in the soil is "broken" and the movement of water out of the soil via evaporation is reduced (James, 1945; Ladewig, 1951). It is generally accepted that the primary benefit from dust mulching comes from the destruction of weeds around the crop and not a reduction in evaporation at the soil surface (Rowe-Dutton, 1957).

Organic-based mulches such as plant waste, straw, sawdust, and manure have also been used to a great extent for vegetable production. Traditionally, organic mulches have consisted of materials which are locally plentiful. Organic-based mulches can be as diverse as the region in which they are used. For instance, banana (*Musa* sp.) leaves and water hyacinth [*Eichhornia crassipes* (Mart.) Solms] have been used for mulching tomato (*Solanum lycopersicum* L.) in Bangladesh (Kayum et al., 2008), while cane (*Saccharum officinarum* L.) bagasse (sugarcane stalks) have been used in Hawaii (Gilbert, 1956) and sawdust in Pennsylvania (Isenberg and Odland, 1950). When applied as a thick layer, organic-based mulches can effectively suppress weeds and increase soil moisture levels (Diaz-Perez et al., 2004). However, research dating to the late 19th century has shown variable results of organic mulches on yield. In areas with warm temperatures and limitations on water for plant growth, straw mulches have been found to positively affect growth and yields of several cucurbits (Emerson, 1903). However, when used in cool climates, the addition of straw mulch, while beneficial for controlling weeds, has been shown to retard the growth of warm season vegetables and decrease yields (Rowe-Dutton, 1957). Nonetheless, organic mulches remain popular due to their low cost and ready availability.

1.2 Paper-based mulches

Paper-based mulches represent some of the earliest mulching systems developed for fruit and vegetable production. Paper was an ideal mulch because it could be transported long distances and easily applied from a roll in the field. Paper-based mulches were extensively used in Hawaii in sugarcane production in the early 20th century. In sugarcane production, lightweight-tar or asphalt-impregnated paper mulches were placed over rows of seed cane and held to the ground with soil. Newly emerged cane shoots were sharp enough to pierce the mulch and continue to grow, while weeds were unable to penetrate the paper and died shortly after germination (Stewart et al., 1926). Using a system remarkably similar to modern plastic mulch, Stewart et al. (1926) evaluated asphalt-impregnated paper for in-row weed control for pineapple [*Ananas comosus* (L.) Merr]. In that trial, the mulches were unrolled over beds using a tractor mounted mulch layer, much like those used today. In addition to reducing weed pressure on the crop, paper mulches generally increased the soil temperature by several degrees Fahrenheit on sunny days, with little effect on cloudy or rainy days (Stewart et al., 1926). Soil moisture and nitrate levels were also generally greater under mulches compared to bare ground leading to enhanced pineapple production (Stewart et al., 1926).

Paper-based mulches were utilized through much of the early 20th century with positive results. Thompson and Platenius (1931) reported positive results with paper mulches in several vegetable crops including pepper (*Capsicum* sp.), tomato, and muskmelon (*Cucumis melo* L.). Paper mulches controlled weeds, increased soil temperatures and moisture levels, resulting in greater yields (Thompson and Platenius, 1931). By altering the growing environment, black-paper mulches affected root distribution of several vegetable crops when compared to bare-ground production (Knavel and Mohr, 1967). The use of paper mulches, particularly those impregnated with asphalt or tar, suppressed weeds, conserved moisture, and warmed the soil, increasing yields in most warm-season crops. However, issues with cost and durability led to the development of alternative mulches.

1.3 Other mulches

In addition to paper and organic mulches several other substances were evaluated through the early and mid 20th century. Aluminum foil was shown to be an effective mulch, increasing yields (Burgis, 1950). The reflective nature of aluminum foil mulch actually cooled soil, while affecting insect predation and the spread of some insect-transmitted diseases (Adlerz and Everett, 1968; Burgis, 1950; Wolfenbarger and Moore, 1968). However, while effective and more durable than paper, aluminum foil mulches were never implemented on a large scale due to high costs.

Petroleum-based spray mulches were also evaluated as an in-row band for cucurbits grown in Florida (Nettles, 1963). These spray mulches functioned as an effective pre-emergent herbicide and warmed the soil. Early and total season yields were significantly greater for petroleum mulches compared to a bare-ground control (Nettles, 1963; Takatori et al., 1963). Despite success with cucurbits, petroleum spray mulches were found to be no more effective than non-mulched controls for potato production (Hensel, 1968).

2. Polyethylene mulch

Invented in its solid form in 1935 by British chemists Fawcett and Gibson, and first made into a sheet form in 1938, polyethylene has changed vegetable production around the world (Lamont et al., 1993; Lamont, 1996; Partington, 1970; Wright, 1968). Much of the pioneering research using low density polyethylene (LDPE) mulch was conducted by Dr. Emery Emmert in the 1950s at the University of Kentucky. In his earliest research, Emmert utilized 0.0015 gauge (1.5 mil-thick) black and black-aluminum pigmented plastic sheets. Transplanted tomatoes and direct-seeded pole beans (*Phaseolus* sp.) were some of the first crops tested with plastic mulches (Emmert, 1956; Emmert, 1957). Irrigation was achieved by cutting furrows in the ground next to the crop, covering with plastic, and cutting holes in the plastic for the water to penetrate the plant bed. In the earliest trials with plastic mulches, Emmert found similar results as previous researchers observed with paper mulches. Weed control and yields, particularly early in the season, were significantly better in treatments grown using the plastic mulch compared to a non-mulched control. In some treatments, Emmert reported an increase in yield of more than 200 bushels/acre (5000 kg/ha) for pole beans grown on plastic compared to a bare-ground control (Emmert, 1957). Although expensive, Emmert estimated that if the plastic material lasted four years in a field, the annual cost would be approximately $12-$16 per acre per year (Emmert, 1957).

Much early research evaluated the effect of mulches on yields and microclimate. Soil temperatures were generally higher under black and clear plastic mulches than non-mulched controls (Army and Hudspeth, 1960; Clarkson and Frazier, 1957; Harris, 1965; Nettles, 1963; Oebker and Hopen, 1974; Takatori et al., 1964). Moisture and nitrate levels were generally greater under plastic mulches (Clarkson, 1960; Harris, 1965). This led to earlier (7-14 day) and greater yields in most crops tested (Clarkson and Frazier, 1957). Interestingly, much of the earliest research with plastic mulches indicated that they altered the soil-root zone microclimate in a similar manner as previously reported for asphalt-impregnated paper mulches in the 1920s and 1930s. However, unlike early paper mulches, the plastic-mulch production system has become the dominant mulching tactic for vegetable production.

2.1 Equipment for the plastic-mulch production system

Early plastic mulches were placed in the field by hand; however, to increase efficiency, specialized equipment was developed. Initial land preparation is similar for bare-ground and plastic-mulch production systems. Soil is ploughed and disked until a fine tilth is achieved. A piece of equipment which can form a raised bed and lay plastic mulch in a single operation is pulled through the field to form the planting bed. When using a raised-bed plastic-mulch system, rows must be spaced further apart in order to accommodate the bed shaping equipment than would be necessary in a flat-bed system. Therefore, raised-bed plastic-mulch rows are typically spaced on 1.7 to 2.2 m centers. Raised beds are often preferred with plastic mulches because they warm quicker than flat beds and offer superior drainage (Lamont, 1996; Tarara, 2000). Herbicides which must be incorporated with tillage may be applied to the soil prior to bed formation or under the mulch while it is being laid in the field. Chemical fumigants are often knifed into the soil under plastic mulches during this process as well (Hartz et al., 1993). Fumigation is an important component of many plastic-mulch production systems. Fumigants have the ability to kill weed seeds, which may potentially germinate, as well as control soil pathogenic fungi, bacteria, and nematodes (Goring, 1962; Wilhelm and Paulus, 1980). Drip irrigation tubing is placed under plastic mulch during the same process. Early research with plastic mulches was conducted using overhead irrigation or furrow irrigation (Emmert, 1957); however, with the introduction of drip irrigation in the 1970s, the vast majority of plastic-mulch production now utilizes this method (Hartz, 1996). The combination of drip irrigation with plastic mulch has significantly increased irrigation water use efficiency in vegetable production (Howell, 2001).

After the plastic is laid in the field, transplants can be placed by hand or using a mechanized transplanter. Plastic mulches must fit tightly against the soil; not only to obtain the maximum benefit of heat transfer from mulch to soil; but also because warm air, when trapped under the mulch, can escape through the holes where transplants are placed, desiccating and damaging the crop (Lamont, 2005). Due to the increased productivity of plastic mulches, in-row spacing of plants is often less compared to bare-ground production systems. Crops which may normally be planted in a single row fashion when grown without mulches are often planted in double rows with plastic mulches (Lamont, 1991). Plant populations per unit area may also be increased in plastic-mulch production systems.

At the end of the growing season, plastic mulches must be removed from the field; though in warmer climates mulches are often double or triple cropped (Hanna and Adams, 1989). Double cropping plastic mulch decreases input costs for growers; however, weed pressures are often increased during the second crop as pre-emergent herbicides have dissipated. Although additional herbicides may be applied to spaces between rows; in-row weeds, growing through the planting holes of the previous crop, can be difficult to control (Waterer et al., 2008). In regions with shorter growing seasons, most plastic mulch is removed after one crop, though double-cropping mulches that have been left in fields over a winter have been evaluated (Waterer et al., 2008). To remove plastic mulch from fields, a specialized piece of equipment (mulch lifter) is required. A mulch lifter is a device which undercuts and lifts plastic mulch out of the soil at which time it can be collected and disposed.

2.2 Characteristics of plastic mulches

The earliest plastic mulches evaluated were 1.5 mil-thick and black (Emmert, 1957). There are now arrays of mulches available. The most common mulches are 1.0 or 1.25 mil-thick and are sold on a 1.2 m-wide roll, though widths of 0.9 – 1.5 m are also produced. Mulches that are thinner than 1.0 mil are easily punctured by weeds. Most degradable plastic mulches are 0.5-0.75 mil-thick, which allows for quicker decomposition. Rolls of mulch commonly range from 730 – 1830 m in length. Mulches may be smooth or embossed. Mulches that are embossed tend to resist excessive expansion and contraction which can cause mulches to become loose from raised beds (Lamont, 1993).

2.3 Colored mulches

The most popular plastic mulch world-wide is black, though white-on-black and clear mulches are also used (Schales, 1990). Other colors that that have been evaluated include: blue, green, red, yellow, brown, white, and silver (Brault et al., 2002; Gough, 2001; Hanna, 2000; Ngouajio and Ernest, 2004). Different colored mulches have multiple effects on the crops being grown. The optical properties of various colored mulches can influence soil and air temperatures around the crop as well as impact weed growth under the mulch. Moreover, in some cases, colored mulches can alter insect behaviour, which can directly (insect feeding) and indirectly (vectoring diseases) affect crop growth. Colored mulches can be separated into those that do not discriminate between different wavelengths of light transmitted and those that selectively prevent transmission of photosynthetically active radiation (PAR) (400-700 nm) (Ngouajio and Ernest, 2004; Tarara, 2000). Mulches that selectively filter out light in the PAR range are called infrared transmitting (IRT) mulches. In addition to restricting light of the PAR range, IRT mulches tend to transmit high percentages of light at longer wavelengths (>900 nm). By selectively filtering light in the PAR range and transmitting longer wavelength light energy, IRT mulches allow for greater soil warming while reducing light available for weed growth.

2.3.1 Non-IRT colored mulches effects on light, temperature, and weed growth

The most common non-IRT mulches are black, clear, white-on-black, and reflective silver. A myriad of other colors exist including: yellow, blue, red, and green (Figure 1). These colored mulches comprise a very small portion of the total mulch utilized. Although benefits have been obtained from colored mulches, particularly red in tomatoes (Decoteau et al., 1989), some allow excessive light transmittance, resulting in unacceptable weed growth. The potential for weed growth and higher costs associated with colored plastic mulches has limited their use.

Fig. 1. Muskmelons being grown on blue, brown, red, and white-on-black mulches[1].

As would be expected, clear mulches transmit the most shortwave radiation (84%) and absorb the least (5%) (Ham et al., 1993). Clear mulches also reflect a high percentage (88%) of long-wave radiation. Clear-plastic mulches increase soil temperatures from 4.4 – 7.8 °C when measured at a depth of 5 cm below the soil surface (Lamont et al., 1993). However, the ability of clear mulch to heat the soil also depends on how it is applied. As noted, clear mulches largely transmit shortwave radiation and reflect long-wave radiation. When clear mulches are loosely applied, long-wave radiation emitted from the soil becomes trapped under the plastic creating a greenhouse-type environment (Ham et al., 1993; Lamont, 1993; Liakatas et al., 1986). However, if the clear mulch is placed tightly on the soil surface, then less convective heating occurs and soil temperature increases may not be as large as expected (Ham and Kluitenberg, 1994; Ham et al., 1993). Diurnal temperature fluctuations are also greater in clear plastic that has not been held tightly to the soil compared to those that have (Tarara, 2000). It has also been reported that the warming effects of clear mulches compared to other colors are substantially reduced in overcast or cloudy environments with less solar radiation (Johnson and Fennimore, 2005).

Clear plastics are utilized for soil solarization. This is the process by which light energy from the sun is trapped, heating the soil enough to cause thermal degradation of bacterial, nematode, fungal, or weed pests (Katan, 1981b; Katan and DeVay, 1991). Soil is prepared for the crop of interest and then solarized for a period of time prior to planting. Disturbing the soil after solarization reduces weed control. When soils are disturbed after solarization, weed seeds that were deep in the soil and unaffected by the treatment, can be brought to the surface to germinate. Clear plastic is the best choice for solarization due to superior heating ability. Reports from California show soil temperatures, measured at a depth of 5 cm from the surface, reaching 60 °C under clear plastic (Katan, 1981a; Katan, 1981b). Plastics are applied more loosely for solarization than they are when mulching plant beds. This may explain the higher temperatures observed in solarization trials than when using clear plastic as a mulch. Solarization has been documented to control a variety of weed pests in many crops (Basavaraju and Nanjappa, 1999; Katan and DeVay, 1991; Law et al., 2008; Megueni et

[1] Photos courtesy of Dr. John Strang, University of Kentucky, Department of Horticulture.

al.; Standifer et al., 1984). However, to properly solarize soil, clear plastic must be exposed to high light and temperatures for a fairly long period of time; therefore, its use is limited in cooler climates (Katan and DeVay, 1991).

Clear plastic functions well for soil solarization, but its use as a mulch is limited. Higher yields have been reported for crops such as strawberries (*Fragaria* sp.) when using clear plastic in combination with soil fumigation with methyl bromide and chloropicrin (Johnson and Fennimore, 2005). However, due to the methyl bromide phase-out and the absence of suitable replacements (Locascio et al., 1997), the ability to control weeds under clear-plastic mulches has limited their use. In non-fumigated soils, clear mulches only controlled 64% of weeds compared to black mulches (Johnson and Fennimore, 2005). Clear plastic is generally unsuitable as a mulch unless supplemental herbicides or fumigants are applied to control weeds (Lamont, 2005).

Black plastic is the predominate mulch utilized in vegetable production today. Much of this popularity is due to a lower cost per acre compared to other mulches. However, black-plastic mulch also effectively warms the soil, improving early crop production and eliminates most in-row weed growth. Unlike clear mulches, black plastic absorbs nearly all shortwave radiation to heat the soil (Ham et al., 1993). By absorbing radiation, black-plastic mulch heats the soil through conduction. A tightly formed plant bed where the mulch makes consistent contact with the soil is necessary for optimal soil warming (Lamont, 1993; Tarara, 2000). By absorbing nearly all shortwave radiation, the surface temperatures of black plastic mulches can reach 55 ^{o}C (Tarara, 2000). Soil temperatures 10 cm under the mulch may increase 3-5 ^{o}C (Ham et al., 1993). Once crop canopies develop, shading of the mulches increases, and soil temperatures under mulches often decrease compared to bare-ground treatments. Though weed seeds may germinate under black-plastic mulch, subsequent weed growth is limited, with the notable exception of yellow and purple nutsedges (*Cyperus* spp.) (Patterson, 1998). Therefore, black plastic is the mulch of choice for early season vegetable production.

White-on-black and silver-reflective plastic mulches are less popular than black plastic, but still serve an important role in vegetable production and weed management. During periods when soil temperatures are elevated, warming the soil with black-plastic mulch can actually harm plants and reduce yields. To avoid damaging the crop, but still provide in-row weed control, white and silver reflective mulches were developed. White mulches were largely ineffective for weed control, without the use of fumigants or herbicides, because they transmitted too much light. Ngouajio and Ernest (2004) reported that white mulches transmitted 48% of solar radiation. This level of light transmission led to substantial weed growth under white mulch. Trials where black mulches were painted white demonstrated benefits of a reflective mulch where weeds could be controlled (Decoteau et al., 1988). White and black-colored mulches are now coextruded forming white-on-black mulch. This mulch is popular because it combines the weed control properties of black mulches (Johnson and Fennimore, 2005) with the soil cooling properties of white-reflective mulch. Ham et al. (1993) reported that white-on-black and silver mulches reflect 48%and 39% of shortwave radiation, respectively. The reflection of shortwave radiation can result in slightly lower root-zone temperatures in reflective mulches compared to bare soil (Diaz-Perez, 2010; Diaz-Perez et al., 2005; Ham et al., 1993; Tarara, 2000).

White-on-black and silver mulches reflect significantly more light into the plant canopy than black mulches, though this decreases as the canopy expands. The upwardly reflected light from white or silver mulches decreases the ratio of red to far-red light compared to black mulches (Decotcau, 2007; Decoteau et al., 1988). The alteration of the light microenvironment is thought to lead to greater leaf areas, shorter internodes, and greater branching in plants grown on reflective mulches compared to black plastic (Decotcau, 2007; Decoteau et al., 1988; Diaz-Perez, 2010). However, the impact of the optical characteristics of the reflective mulches is limited at certain heights above the bed, and wanes as the plant canopy forms (Lamont, 2005). It is also difficult to isolate differences in light effects on plant growth from root-zone temperatures when comparing different colored mulches (Diaz-Perez and Batal, 2002). Light reflective mulches have also been suggested to influence insect predation on vegetable crops as well (Brown and Brown, 1992; Caldwell and Clarke, 1999; Csizinszky et al., 1995; Funderburk, 2009; Lu, 1990).

2.3.2 The effect of IRT mulches on temperature, light, and weed growth

IRT mulches allow transmission of light outside of the PAR spectrum. By transmitting infrared radiation, but excluding PAR, IRT mulches combine the soil-warming benefits of clear plastic mulches with the weed control of black plastic mulch. IRT mulches are most commonly manufactured in green and brown colors. Ngouajio and Ernest (2004) reported that IRT-green and IRT-brown mulches transmitted 42% and 26% of light, respectively, between the wavelengths of 400 and 1100 nm. This was compared to just 1% in black and 2% in white-on-black mulches, respectively. However, the green and brown-IRT mulches transmitted 16% and 6% of PAR (400-700 nm), respectively. Ham et al. (1993) reported 37% of total short-wave light (300-1100 nm) transmitted for an IRT mulch, while Johnson and Fennimore (2005) reported 10.6% and 10.9% transmittance of PAR (400-700 nm) for green and brown IRT mulches, respectively. This selective transmittance of light allows IRT mulches to provide similar weed control as black-plastic mulches (Johnson and Fennimore, 2005; Ngouajio and Ernest, 2004).

The soil warming properties of IRT mulches are reported to be more similar to clear plastic mulches (Lamont, 1993). However, effects of IRT mulches on soil temperatures may vary. Ngouajio and Ernest (2004) reported heat accumulation in growing degree days (base 10 ^{o}C) in IRT mulches was similar to black plastic mulch and better than white and white-on-black mulches. In that trial, clear mulches were not included for comparison. Johnson and Fennimore (2005), using a degree-hour model for heat accumulation, reported that IRT brown and green mulches accumulated 5200 and 6300 degree hours, respectively, while clear and black-plastic mulches accumulated 11000 and 4400 degree hours, respectively. This suggests that IRT mulches provide soil warming abilities between clear and black-plastic mulches. However, in the same trial, the authors reported that black-plastic mulch accumulated more degree hours than clear and IRT mulches in a cooler, cloudier location. Ham et al. (1993) trialled several mulches and reported that IRT mulch had similar soil warming characteristics as clear-plastic mulch. However, both IRT and clear-plastic mulches failed to warm the soil as much as a black plastic mulch (Ham et al., 1993). Therefore, while IRT mulches may control weeds as well as black-plastic mulch, the relative soil warming abilities of IRT mulches compared to black plastic may vary based on local climate.

2.4 Polyethylene mulches influence the root zone affecting weeds and crops

Numerous studies show that vegetables grown with plastic mulches typically out yield those grown on bare ground, even with complete weed control for the bare-ground plots. (Table 1). It has been well documented that plastic mulches reduce evaporation, nutrient leaching, and soil compaction in the plant bed (Lamont, 2005). However, the impact of plastic mulch on root architecture and root-zone temperatures are particularly notable; especially as the yield benefits of black plastic mulch are often greater in the spring than in the fall after soil has warmed (Table 1).

Treatmemt	Total Yield [mean ± s.e (kg·ha^{-1})]			
	Spring		Fall	
Black Plastic	37905 ± 1492	a[z]	27214 ± 953	a
Bare ground hand-weeded	19693 ± 1352	b	21843 ± 1214	b
Bare ground non-weeded	10524 ± 722	c	17330 ± 1866	b

[z] Treatments within a column not followed by the same letter are different by Duncan's Multiple Range Test $P<0.05$

Table 1. Yields of summer squash (*Cucurbita* sp.) under black plastic mulch and bare-ground treatments grown in summer and fall [adapted from (Coolong, 2010)].

Knavel and Mohr (1967) reported summer squash, tomato, and pepper plants had significantly more and longer roots when grown with plastic mulches compared to unmulched controls. However in graphic representations, roots under plastic mulches were also significantly shallower and spread out over the surface of the bed compared to bare-ground plots (Knavel and Mohr, 1967). Other trials have reported that plastic mulches influenced adventitious root development, but overall root architecture remained similar compared to bare-ground production (Gough, 2001).

Significant research has been conducted evaluating the impact of mulch type and color on root-zone temperature and subsequent yield impacts (Diaz-Perez, 2009; Diaz-Perez, 2010; Diaz-Perez and Batal, 2002; Diaz-Perez et al., 2005). Generally, black plastic mulch is preferred for spring plantings as a method to warm the root zone and increase yields (Diaz-Perez, 2009; Diaz-Perez, 2010; Diaz-Perez et al., 2005). However, during summer, soil temperatures under black plastic mulches may be greater than 30 °C (Ham et al., 1993; Tarara, 2000; Tindall et al., 1991). Vegetable growth and yield has been shown to respond quadratically to root-zone temperature, increasing up to a point then rapidly decreasing (Coolong and Randle, 2006; Diaz-Perez, 2010; Tindall et al., 1990). Depending on the crop grown, the critical root-zone temperature for maximum yield and growth may be several degrees cooler than is present under the black plastic mulch. Diaz-Perez and Batal (2002) reported an increase of 5-fruit per plant for tomatoes grown in black plastic mulch compared to bare-ground. However, in the same trial, plants grown on reflective gray and silver mulches, which reduced root-zone temperatures compared to black plastic, had an additional 6-7-fruit per plant compared to the black-plastic mulch treatment. Because of high root-zone temperatures, reflective mulches are encouraged for summer-planted crops. To double-crop black plastic mulches during the summer, a system was developed which utilized a photodegradable black mulch placed over a white non-degradable mulch

(Graham et al., 1995). The black mulch warmed the soil in the spring and then degraded, exposing the white mulch used for a second planting. This system was effective in reducing soil temperatures late in the summer; however, a co-extrusion process has not been commercialized for developing such a system.

2.4.1 Mulch type influences weed morphology

Two common weeds that are not controlled by black plastic mulches are purple and yellow nutsedge. These are two of the most problematic weeds for vegetable production in the Southern U.S. (Webster and MacDonald, 2001). Unlike most weeds, both yellow and purple nutsedge have the ability to pierce plastic mulches (Figure 2) and successfully compete with crops (William, 1976; William and Warren, 1975).

Fig. 2. Yellow nutsedge penetrating white-on-black mulch.

Traditionally, growers have relied on fumigation with methyl bromide to control nutsedge when using plastic mulches. However, as methyl bromide use has been phased out with the exception of some critical-use exemptions, the management of yellow and purple nutsedge under plastic mulches has become a pressing issue (Webster, 2005). Interestingly, some research has demonstrated that controlling yellow and purple nutsedge may depend on the light transmittance of mulches used. Purple nutsedge shoot and tuber growth was shown to be greater under white-on-black mulch compared to IRT mulch when grown under sunlight in a greenhouse (Patterson, 1998). However, in the same trial, all mulches failed to prevent nutsedge shoot emergence when treatments were conducted in total darkness in growth chambers. This suggests that the transmission of light may alter the ability of purple nutsedge to penetrate mulches. Chase et al. (1998) reported similar results when evaluating yellow and purple nutsedge. In that trial, yellow and purple nutsedges penetrated black mulches to a greater extent than clear and IRT mulches. All mulches controlled yellow nutsedge to a greater degree than purple nutsedge. The authors theorized that nutsedge rhizomes have a sharp tip that will penetrate opaque mulches. However, upon exposure to light, photomorphogenic initiation of leaf expansion occurs and the leaves do not have the ability to penetrate the plastic mulches as well as the rhizome (Chase et al., 1998). Although nutsedges will sprout under clear or IRT mulches, they rarely penetrate through the film. Webster (2005) reported similar results, also noting the greater relative ability of purple compared to yellow nutsedge to overcome any plastic mulch. Over time, this may result in a shift in the weed population from yellow to purple nutsedge in mulched vegetable cropping systems (Webster, 2005).

3. Waste issues and mulches

Although plastic mulches provide excellent in-row weed control and enhance productivity of many vegetable crops, waste is a significant issue. It is estimated that world-wide plastic film use is 700,000 tons per year (Espi et al., 2006) with more than 140,000 tons used annually in the U.S. (Shogren, 2001). Most of these mulches end up in landfills or are burned (Hemphill Jr, 1993; Kyrikou and Briassoulis, 2007). As landfill space becomes limited and concerns rise about discarding plastic, which may potentially contain pesticide residues, disposal of mulch films has become a significant issue for farmers. Recycling is not typically an option as used mulches contain dirt and debris from production fields that must first be removed prior to the recycling process. At this time, processes to remove dirt from mulches are too expensive. An alternative to recycling that has been pilot-tested was to compress used-plastic mulches into dense pellets and using them as a fuel source. These pellets have been effectively co-fired with coal in trials conducted at Pennsylvania State University (Lawrence et al., 2010). Plastic mulches are petroleum-based products and contain roughly the same energy content as fuel oil on a weight basis (Hemphill Jr, 1993). In addition to environmental concerns, the costs for removal and disposal of plastic mulches are approximatley $250/ha (Waterer, 2010).

3.1 Degradable mulch films

Economic and environmental concerns have spurred interest in degradable mulch films. Designing degradable mulches with properties similar to LDPE is challenging. The degradable mulch must be flexible, lightweight, prevent light transmittance, and degrade in a timely manner after harvest. Exposure to light, temperature, and moisture can influence degradation (Kyrikou and Briassoulis, 2007). Normalizing degradation rates between growing regions with vastly different climates is a challenge as well. Some crops will quickly form a canopy shading mulches and thus delaying degradation; while others do not. Developing a mulch that will degrade on-demand at a competitive cost is a challenge.

Degradable plastic mulches are often labeled as biodegradable. However, to be considered biodegradable, a polymer must be completely converted by microorganisms to water, minerals, carbon dioxide and biomass (Kyrikou and Briassoulis, 2007). Some mulches that have been marketed as biopolymers do not biodegrade, but fragment, leaving synthetic polymers in the environment in microscopic fragments. Starch-polymer blends fragment as the starch co-polymers degrade, with the synthetic co-polymer remaining in the field (Halley et al., 2001). It is debated whether the synthetic polymers which are left in the field biodegrade. Nonetheless, a variety of mulches have been developed that are reported to completely degrade.

Halley et al. (2001) developed a mulch film using modified-starch polymers that performed as well as a conventional polyethylene mulch for pepper production. This mulch withstood 14 weeks of water exposure and remained largely stable during crop production. However, just two weeks after the mulch was plowed into the soil, it was visually undetectable, with composting trials indicating that the mulch completely degraded to carbon dioxide and water after 45 days (Halley et al., 2001). Waterer (2010) tested clear, black, and wavelength-selective starch-based mulches. In this trial, clear and wavelength-selective starch-based mulches degraded quickly in the field. The clear starch-based mulch broke down completely within 8 weeks of application. Although weed growth occurred in the clear and wavelength selective-starch mulches, the yields of the crops trialled (zucchini, cantaloupe, pepper, eggplant, and corn) were not significantly different between mulch types (starch-based polyethylene) of a given color (clear, wavelength-selective, black). The black-colored starch mulch remained intact for the entire growing season (Waterer, 2010). This trial was conducted at a northern latitude (Saskatoon, Saskatchewan, CA) with a short cool growing season. Different results may be expected in warmer environments.

Another commonly utilized polymer for degradable mulches is polybutylene adipate-co-terephthalate (PBAT). PBAT is reportedly a fully biodegradable polymer that has similar physical characteristics as traditional LDPE mulches, although, PBAT mulches are typically slightly thinner and tear easier than common LDPE mulches (Kijchavengkul et al., 2008a; Witt et al., 2001). During the time PBAT mulches are set out in the field for crop production they begin photodegrading with a period of intensive biodegradation after crop removal and subsequent plowing into the ground. However, the absolute biodegradability of the PBAT mulches has been questioned due to cross-linking that can occur between benzene rings contained in the PBAT polymer (Kijchavengkul et al., 2008a; Kijchavengkul et al., 2008b). Typically, white or green PBAT mulches have been found to degrade quicker than black mulches, often breaking apart while the crop is in the field (Moreno and Moreno, 2008; Ngouajio et al., 2008). White-colored PBAT films can contain titanium oxide, which may catalyze photodegradation leading to premature breakdown (Gesenhues, 2000; Kijchavengkul et al., 2008a). Black-colored PBAT mulches typically last longer and it is proposed that the carbon black added to the PBAT film absorbs light energy, reducing photodegradation (Kijchavengkul et al., 2008a; Schnabel, 1981).

Trials of PBAT mulches indicate that white-colored PBAT mulches have lower yields compared to black-polyethylene mulches, but black-PBAT mulches usually perform as well as traditional polyethylene mulches (Miles et al., 2006; Moreno and Moreno, 2008; Ngouajio et al., 2008). Usually white-PBAT mulches break down prematurely allowing weeds to grow, affecting crop yields. Interestingly, soil temperatures under black-PBAT mulches are often lower than under black-polyethylene mulches (Moreno and Moreno, 2008; Ngouajio et al., 2008). Although promising, PBAT and starch-based mulches are not used on a large scale at this time.

3.2 Degradable paper mulches

Nearly 100 years after the use of paper mulches was documented in Hawaii, they are again being evaluated for use in vegetable production (Stewart et al., 1926). Paper is a renewable resource that readily biodegrades. Newspaper-based mulches represent an available and cost effective resource and have been frequently trialled; though they often deteriorate rapidly under field conditions, reducing effectiveness (Shogren, 2001). Shredded newspapers have been successfully used as a weed suppressing mulch in organic high-tunnel cucumber production (Sanchez et al., 2008). A high-tunnel environment (no wind or rain) is conducive for using newspaper mulches. Traditionally, paper mulches degrade quickly under field conditions and may tear when using traditional mulch-laying and planting equipment (Coolong, 2010). To improve the durability of paper-based mulches, several trials have utilized mulches with polyethylene, wax, or vegetable oil coatings used to slow degradation of paper mulches in the field (Shogren, 1999; Shogren and David, 2006;

Shogren and Hochmuth, 2004; Vandenberg and Tiessen, 1972). Coating 30-40 lb (14-18 kg) kraft paper with vegetable oils will retard degradation by repelling water and also by filling voids in the cellulose fibers of paper, preventing microorganism infiltration (Shogren, 1999). When oils are applied to the kraft-paper mulches, field-life can be increased to 14 weeks; giving adequate weed control and yields comparable to black-plastic mulch (Shogren, 1999; Shogren and David, 2006). Coolong (2010) reported adequate weed control and yields comparable to black plastic mulches for 40-lb kraft paper coated with a thin layer of clear polyethylene. Mating a thin degradable coating to paper mulch may be a potential solution to the premature degradation of paper mulches; however, the weight and subsequent shipping costs for paper-based mulches at the present time precludes them from widespread use.

4. Summary and conclusions

Mulches have been used for centuries for weed control in vegetable crops. Despite the development of a range of herbicides available, mulches still continue to play a significant role in the production of vegetable crops. The introduction of polyethylene mulches in the 1950s significantly altered the way mulches were utilized. When combined with tillage techniques and herbicides, plastic mulches allow vegetable growers to maintain nearly weed-free fields. The ability of plastic mulches to alter crop microclimate can also lead to improved earliness, quality, and yields (Lamont, 2005). Plastic mulches are now an indispensible part of the modern vegetable production system. However, as concerns regarding the environmental impact of the disposal of mulches increase, alternatives are being sought. Paper-based mulches are degradable and made of a renewable resource, but are bulky and costly to produce. Organic mulches such as straw improve soil health by increasing organic matter and improving soil structure. However, they do not provide the same soil warming benefits as polyethylene mulches. This may limit their use in certain crops or cooler climates. As technologies improve, a completely degradable mulch film made from natural polymers may replace traditional polyethylene mulches. However, until that time polyethylene plastic will remain the most widely used mulch for the production of warm-season vegetable crops.

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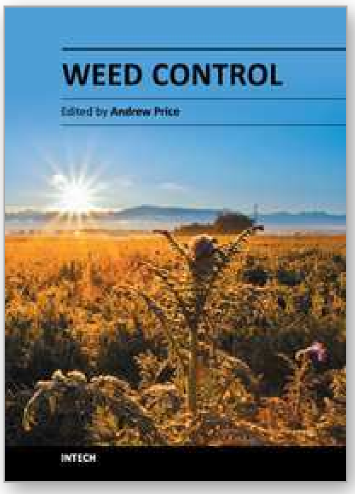

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Crop loss due to weeds has challenged agricultural managers since man began to develop the first farming systems. In the past century, however, much progress has been made to reduce weed interference in crop settings through effective yet mostly non-sustainable weed control strategies. With the commercial introduction of herbicides during the mid-1900's, advancements in chemical weed control tactics have provided efficient suppression of a broad range of weed species for most agricultural practices. Currently, with the necessity to design effective sustainable weed management systems, research has been pushing new frontiers on investigating integrated weed management options including chemical, mechanical as well as cultural practices. Author contributions to Weed Science present significant topics of research that examine a number of options that can be utilized to develop successful and sustainable weed management systems for many areas of crop production