The Use of Biodegradable Mulches in Pepper Production in the Southeastern United States

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Abstract. Plasticulture systems with polyethylene (PE) mulch and drip tape are common for production of peppers (*Capsicum annuum* L.) in the United States because of their soil warming, moisture conservation, and other advantageous effects. However, disadvantages include disposal costs and plastic pollution of the environment and temperature stress in warm climates with black mulch. Use of biodegradable plastic mulches (BDMs) is becoming more common, as they provide the same benefits of PE mulch without the disposal problems. In 2017 and 2018, we conducted experiments in Knoxville, TN, comparing production of pepper fruit with five different BDM [one white-on-black (WOB) and four black], one black PE mulch, one brown creped, paper mulch, and bare ground control treatments. We also measured the durability and effectiveness of weed suppression of the different mulches over the growing season compared with a hand-weeded bare ground control. Most mulches were degraded, with 40% to 60% of the soil exposed by the end of the season, with the exception of the paper mulch, which was completely degraded at the end of both seasons. Yields were similar among treatments in 2017, with the exception of Naturecycle, which had the lowest yield. Weed pressure was severe, especially in 2018, largely due to early penetration of all mulches except paper by nutsedge. Due to the early and season-long weed pressure and heat stress in black mulches, there were fewer healthy plants in all black-colored mulch treatments in 2018, leading to reduced yields in these treatments. Paper mulch was the only treatment that prevented nutsedge growth; therefore, this treatment and the hand-weeded bare ground treatment had the greatest yields in 2018. WOB also had yields comparable with paper and bare ground plots in 2018, likely due to the cooling effect of the white mulch. The results suggest that in hot climates and in fields infested with nutsedge, paper mulches perform best for midseason pepper cultivation due to the cooling effects and superior weed control.

Most bell peppers (*Capsicum annuum* L.) produced in the United States are grown on raised beds with drip irrigation and PE mulch, and the production value has increased from \$514 million in 2012 to more than \$641 million in 2017 (USDA NASS, 2018). PE mulch can be beneficial for intensive vegetable and specialty crop production by increasing yields and fruit quality, reducing weed pressure, warming the soil for early season production, and reducing water evaporation

from the soil (Gao et al., 2019; Kasirajan and Nguajio, 2012; Lamont, 2005). Data on US and worldwide usage of PE mulch are difficult to find. It is reported, however, that China leads the world in PE mulch use, with a nearly 5-fold increase from 3×10^5 tons in 1991 to 14.7×10^5 tons in 2017 (Gao et al., 2019).

Although PE mulch has many advantages, there are also growing disadvantages, largely due to disposal challenges and potential soil and water contamination. Removal from the field is labor intensive, and disposal is becoming increasingly difficult as labor costs, landfill tipping fees, and fuel costs for transport to landfills increase. With increased costs for landfill disposal, the environmental costs of growers illegally disposing of mulch may be increasing as well. Burying or tilling PE mulch into the soil can lead to contamination of the soil and groundwater with plastic byproducts and microplastics (He et al., 2015; Wang et al., 2013).

Geyer et al. (2017) report that in the past 65 years plastics production has increased faster than any other manufactured material, and although there has been extensive research of microplastics in aquatic ecosystems, effects of plastic in terrestrial ecosystems are

largely unknown (Brodhagen et al., 2017; Rillig, 2012). There are some reports, however, that plastic residues also may be harmful to soil ecosystems (Bläsing and Amelung, 2018; Steinmetz et al., 2016). A meta-analysis by Gao et al. (2019) found that plastic film residue in soil at or below 240 kg/ha did not affect crop yield, but when plastic residue was greater than 240 kg/ha, yield was significantly reduced.

BDMs provide many of the same benefits as PE mulch while avoiding these disposal problems, as they can be tilled into the soil at the end of the season or retrieved and then composted. Jambeck et al. (2015) estimate that if the top 20 countries (ranked by mass of improperly managed plastic waste) were to increase proper disposal of plastic waste, the mass of waste potentially polluting terrestrial and aquatic environments could decrease 41% by 2025. Changing from PE to BDM could help the agricultural industry reach this needed reduction in plastic waste.

As mentioned, a major benefit of PE mulch and BDM is usually reduced weed pressure; however, nutsedge species [purple nutsedge (*Cyperus rotundus* L.) and yellow nutsedge (*Cyperus esculentus* L.)] can penetrate both PE mulch and BDMs (Webster, 2005). Purple nutsedge is a pernicious weed and has been reported from more locations in the world than any other weed, affecting 52 different crops in 92 different countries (Holm et al., 1977). Sometimes the only economical option available to growers with nutsedge-infested fields is to abandon high-value vegetable crops for a cereal or forage crop that can better compete with the weed (Cirujeda et al., 2012; Wang et al., 2009). Webster (2005) observed that PE mulch use can actually lead to expansion of underground purple nutsedge patches compared with non-mulched controls and that tears and holes caused by nutsedge allow other weeds to germinate.

Nutsedge can be especially harmful for pepper production, as emergence of only five yellow nutsedge plants per m² can reduce bell pepper yield by 10% (Motis et al., 2003). Weeds such as nutsedge pose a significant challenge to successful use of PE mulch and BDMs for vegetable production. In fact, if a field is infested with nutsedge, a grower may not be able to successfully use PE mulch or BDMs. Numerous field studies have examined ways to control nutsedge in PE-mulched peppers (e.g., Bangarwa et al., 2009; Motis et al., 2003, 2004; Santos et al., 2007). One study has shown that coated paper mulch can reduce nutsedge pressure in pepper (Shogren and David, 2006). Others have also observed that paper mulch is one of the few mulches that can effectively suppress nutsedge in other crops (Anzalzone et al., 2010; Cirujeda et al., 2012; Shogren and Hochmuth, 2004), as nutsedge can penetrate plastic mulch four times as thick as commonly used commercial mulches (Webster, 2005).

For BDMs to be a viable alternative, they must provide similar benefits to PE without the disposal and environmental issues. The

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objectives of this study were to 1) compare the yield of pepper fruit among five different BDMs compared with PE mulch, paper mulch, and bare ground treatments and 2) measure the durability and effectiveness of these mulches for weed suppression over the growing season compared with a hand-weeded bare ground control.

Materials and Methods

Experimental location. This study was carried out in 2017 and 2018 at the University of Tennessee, East Tennessee AgResearch and Education Center, Plant Sciences Unit in Knoxville, TN (lat. 35°52'52" N, long. 83°55'27" W, elevation 270 m). The field site was located in the subtropical southeast United States with an average daily temperature of 23 °C, an average relative humidity (RH) of 73%, and an average rainfall of 421 mm (30-year average; Arguez et al., 2010). The site has moderately well-drained Shady-Whitwell complex soil characterized as a fine-loamy, thermic Typic Hapludult with a pH of 6.4 and 1.3% organic matter. A winter wheat cover crop preceded the experiment both years, and other records of field history for 2015 to 2016 can be found in Ghimire et al. (2018).

Experimental design and planting. The mulch treatment plots were established in 2015 in a completely randomized block design with four replications. Treatment plot assignments did not change across the years (2015–2018) to avoid cross-treatment mulch and soil contamination as BDMs are tilled into the soil at the end of every cropping season. Eight treatments (Table 1) were randomized within each main plot in 2015. The 2015 and 2016 experiment, with pumpkin as the test crop, is described in Ghimire et al. (2018). The WOB mulch treatment, with the white surface facing up and the black surface touching the soil, was added in 2017 replacing a BioAgri treatment that was removed from the field at the end of the seasons in 2015 and 2016. Mulch was laid by machine (Model 2600 Bed Shaper; Rain-Flo Irrigation, East Pearl, PA) in all plots at the time of bed shaping on 23 May 2017 and 24 May 2018. ‘Aristotle’ pepper (a green bell, Seedway, LLC, Hall, NY) was planted both years and was chosen for its resistance to bacterial

leaf spot races 1 to 3 and tolerance to *Phytophthora* and *Tobamovirus*. Plots were five beds wide and 9-m long, and beds were spaced 2.1 m center-to-center, which is greater than typical grower production practices in this area due to concurrent experiments as described previously. In-row spacing was 0.46 m with plants in a double staggered row, with 18 plants per row and 36 plants per plot. Peppers were seeded in the greenhouse in 128-cell trays on 21 to 22 Apr. 2017 and 16 to 17 Apr. 2018, and transplanted in the field on 25 May 2017 and 29 May 2018. Following transplanting, the remaining plants were moved to 54-cell trays and kept in a greenhouse for replacing missing or dead transplants in the field for up to 4 weeks following the initial transplant date. At the end of each season (2015–18), the PE was removed from the field, and BDMs and paper mulch were tilled into the soil.

Fertilizer and irrigation. After disking the field, 56 kg N/ha, 112 kg P/ha, and 112 kg K/ha were broadcast over the entire field with a 3-m drop spreader, then the field was worked with a field cultivator to incorporate the fertilizer and prepare an even seedbed for planting. Drip irrigation tape (T-Tape, Model #508-08-340, 0.20 mm, 20-cm emitter spacing, 4.23 L/min/100 m flowrate, San Diego, CA) was laid simultaneously with the mulch treatments. Weekly fertigation applications of calcium nitrate (28 kg/ha rate) and potassium nitrate (22 kg/ha rate) were applied starting within a week after transplanting and continuing until the last harvest for a total of 43 kg N/ha and 62 kg K/ha applied through fertigation each season.

Weather data. Air temperature, rainfall, and RH were collected from the Plant Sciences Unit weather station, which was 10 m away from the pepper field. The precipitation sensor on the field weather station was malfunctioning at times during both growing seasons, so precipitation data were taken from the U.S. National Oceanic and Atmospheric Administration station located on the farm 533 m from the field site (NOAA, 2018). Soil temperature and moisture sensors (5TM; Decagon Devices, Inc., Pullman, WA) were installed in bed 3 of each plot in one replicate block at 10 cm and 20 cm depths and data were recorded at 60 s intervals and averaged hourly using data loggers (EM50G; Decagon Devices, Inc.).

Weed management. Planting holes, bed shoulders, and bare ground plots were hand weeded as needed throughout both growing seasons, from 7 June through 1 Aug. 2017 and 5 June through 26 July 2018. Weeds in alleys were controlled with herbicides (RoundUp WeatherMax; Monsanto, St. Louis, MO, 2.3–2.9 L·ha⁻¹).

Mulch deterioration ratings and weed assessments. Mulch degradation in each plot during the cropping season was rated visually, two times per month (about on the first and 15th of each month). Ratings were done by the same person for consistency both years. Mulch degradation was assessed each time as percent soil exposure (PSE), where 0% represents completely intact mulch and fully covered soil and 100% represents fully exposed soil. Rating was in 1% increments until 20% exposure and in 5% increments thereafter. PSE was measured in the center 1 m of bed 3 in each plot.

Weed data were collected from a 1-m block of either bed 2 or 4 (determined through randomization) three times during each season: 3 weeks after transplanting, midseason, and ≈2 weeks before the last harvest. The first sample was in the center of the bed, the second was east of center, and the last was west of center so that a new area was sampled for each rating. Weeds were clipped at the soil surface and counted by species. Total fresh aboveground biomass for all weeds combined per plot was recorded. Samples were then dried at 62 °C for 48 h to determine total dry mass.

Plant health ratings. Plant health was rated on 11 July and 9 Aug. in 2017 and on 3 July and 14 Aug. in 2018. All plants in the data bed were visually classified as healthy (full, dark green canopy), small but otherwise healthy (dark green canopy, but noticeably small), stunted (poor color, very small), or dead/missing.

Fruit harvest and yield. Peppers were harvested at the mature green stage weekly 26 July to 19 Sept. 2017 and 16 July to 27 Aug. 2018 from all plants in the center bed of each plot. Marketable pepper fruit were sorted into size classes: small (<7.0 cm), medium (7.0–7.6 cm), large (7.6–8.9 cm), extra large (8.9–10.2 cm), jumbo (>10.2 cm), and choppers (fruit that are smaller or misshapen but otherwise marketable). Fruit in all size classes were then

Table 1. Mulch treatments in BDM field experiment in Knoxville, TN, 2017–18.

Treatment	Manufacturer	Thickness (μm) ²	Key product ingredient(s)	Product color
1. Bare ground				
2. Polyethylene (PE)	Filmtech, Allentown, PA	25.4	Polyethylene	Black
3. WeedGuardPlus (WGP)	Sunshine Paper, Aurora, CO	240.0	Creped paper	Light brown
4. Bio360	DuBois Agrinovation, Saint-Rémi, Quebec, Canada	18.0	Polyesters blends with or without starch	Black
5. Organix A.G., black	Organix Solutions, Maple Grove, MN	17.8	BASF Ecovio (PBAT + PLA)	Black
6. Naturecycle	Custom Bioplastics, Burlington, WA	25.4	Starch–polyester blend	Black
7. Exp-PLA/PHA	Experimental Film ³	25.0	Ingeo PLA/Mirel amorphous PHA	Black
8. Organix A.G., White-on-black (WOB)	Organix Solutions, Maple Grove, MN	17.8	BASF Ecovio (PBAT + PLA)	White on top, black on bottom

²Divide by 25.4 to convert to mils.

³Prepared for this project by Metabolix, Inc., Cambridge, MA.

BDM = biodegradable plastic mulch; PBAT = poly(butylene adipate-co-terephthalate); PLA = polylactic acid; PHA = polyhydroxyalkanoate.

counted and weighed. Culls were sorted by primary cause of unmarketability, then were counted and weighed by category. Unmarketable categories included sunscald, insect damage, disease, blossom end rot, rot or other (too small, immature, mechanical or string damage, nutsedge damage, broken branches, russetting, animal damage, and checking).

Data analysis. All data were subjected to analysis of variance using generalized linear mixed model (GLIMMIX) procedure in SAS (Statistical Analysis System Version 9.2 for Windows; SAS Institute, Cary, NC). Data were analyzed as a completely randomized block design. The MMAOV macro (Saxton, 2010) in SAS was used to build all PROC GLIMMIX procedures and the slice statement was used to simplify means comparison by dates. The assumption of normality was assessed using the Shapiro–Wilk test ($W > 0.80$) and homogeneity of variances were assessed with Levene’s test ($\alpha = 0.05$). Fisher’s least significant difference test ($\alpha = 0.05$) was used to compare treatment means for significant differences. When treatment by year and treatment by date interactions were significant, data are presented separately by year or date. As no transformation satisfied the assumptions of normality and homogeneity of variance for yield, weed count, and weed dry mass data, a nonparametric transformation (PROC RANK in SAS) was used for mean separations; however, raw means are reported. Percentage data were analyzed using the GLIMMIX procedure in SAS with a binomial distribution.

Results

Weather data. Total rainfall for the growing season (late May to early September) was 481 mm for 2017 and 437 mm for 2018. The 2-year daily average air temperature for the growing seasons was 24 °C and RH was 81%. Daily average, maximum, and minimum air temperature for both seasons are shown in Fig. 1. Daily average soil temperatures (°C) at 10 cm for both seasons are shown in Fig. 2. Soil temperatures were not recorded for the WOB treatment, due to the project’s original instrumentation setup in 2015.

Percent soil exposure. Overall PSE was similar for 2017 and 2018, with most mulches reaching 40% to 60% soil exposed by the end of the season, except for WeedGuardPlus (WGP), which was completely degraded by the end of both seasons (Fig. 3). Another exception was polylactic acid/polyhydroxyalkanoate (PLA/PHA), which broke down much more rapidly in 2018 than in 2017, with a soil exposure of more than 40% only 17 d after transplanting in 2018 and almost 100% soil exposure by the end of the 2018 season (Fig. 3). PE mulch remained the most intact, followed closely by WOB, with both treatments having about 16% to 20% soil exposed by the end of the season in 2017 and just less than 40% soil exposed by the end of the season in 2018.

Weed assessment. There were significant treatment and year as well as treatment, date, and year interactions ($P < 0.0001$ for all). Data are interpreted by treatment with dates and

Fig. 1. Average, maximum, and minimum air temperatures over the 2017 and 2018 growing seasons in Knoxville, TN.

Fig. 2. Average daily soil temperatures (°C) at 10 cm over the 2017 and 2018 growing seasons in Knoxville, TN. PLA = polylactic acid; PHA = polyhydroxyalkanoate.

years separate. In 2017, end of the season weed dry biomass was generally lowest for Bio360 and WGP; intermediate for bare ground, WOB, and PE; and greatest for PLA/PHA, Organix, and Naturecycle (Table 2). In

2018, at the midseason rating, weed dry biomass was lowest for bare ground and WGP as well as PE; intermediate for Bio360, Naturecycle, Organix, and WOB; and greatest for PLA/PHA (507 g·m⁻²) (Table 2). By late

season 2018, the hand-weeded bare ground plots had the lowest weed dry biomass, followed by WGP and PE. Bio360, Naturecycle, Organix, and WOB plots were intermediate, and PLA/PHA plots had the greatest biomass (701 g·m⁻², Table 2).

The most prevalent weed species by count was yellow nutsedge, followed by goosegrass (*Eleusine indica* L.), then redroot pigweed (*Amaranthus retroflexus* L.) (data not shown). Bare ground plots had the greatest species diversity, with an average range of two to six different species of weeds over the 2017 and 2018 weed rating dates (data not shown). In 2018, the early breakdown and lifting of the PLA/PHA mulch by extreme nutsedge pressure led to greater levels of weed diversity, with numbers of different species approaching the diversity in the bare ground plots (4–5 species, data not shown). Early season nutsedge counts were made during PSE ratings (data for bare ground were not recorded), and counts were greater in 2018 than 2017, with PLA/PHA plots having greater counts per m² in 2018 than all

other treatments except Naturecycle. WGP plots had lower counts than all other treatments except Bio360, PE, and Organix with 0 nutsedge per m² (Table 3). Comparing the end of the season data, we found that WGP plot nutsedge counts were lower than for PLA/PHA, Naturecycle, PE, WOB, and Organix plots in 2017 and were lower than any other mulch treatment on 13 June and 21 Aug. 2018 (Table 3). For the plastic treatments, by late season 2017, PLA/PHA, Naturecycle, Organix, PE, and WOB plots all had significant levels of nutsedge penetration (48–84 plants per m²) (Table 3). For the plastic treatments, by late season 2018, Bio360, PLA/PHA, Naturecycle, and Organix had the greatest nutsedge counts (163–173 plants per m²), followed by WOB (99 plants per m²) and then PE (53 plants per m²).

Plant health ratings. On 11 July 2017, bare ground, WGP, and WOB plots had the greatest number of healthy plants, all averaging 34 plants in the data bed (Fig. 4). Bio360, PLA/PHA, Organix, and PE plots averaged 21 to 26 healthy plants in the data

bed. Naturecycle plots had the lowest number of healthy plants, with an average of 14 (Fig. 4). On 9 Aug. 2017, bare ground, Bio360, PLA/PHA, Organix, PE, WGP, and WOB plots were all statistically similar, with 28 to 34 healthy plants per data bed, whereas Naturecycle had significantly less than all other treatments with 19 plants (Fig. 4). On 3 July 2018, bare ground, PLA/PHA, WGP, and WOB plots had a greater number of healthy plants than all other treatments, with 27 to 33 plants per data bed. PE plots had the lowest number, with 7 healthy plants per data bed, but did not differ from Naturecycle and Organix plots (Fig. 4). On 14 Aug. 2018, bare ground plots had the greatest number of healthy plants with 33, although not different from WGP and WOB plots with 30 and 29, respectively. PE plots still had a lower number of healthy plants (5) than all other treatments except Organix with 9 healthy plants per data bed (Fig. 4).

Fruit yield. In 2017, total yield by weight was greatest for Bio360, bare ground, WGP, PE, WOB, and PLA/PHA plots (Table 4). All

Fig. 3. Percent soil exposure (PSE) for all mulch treatments over the pepper-growing seasons in Knoxville, TN, in 2017 and 2018. The error bars represent two SE of the mean. PSE ratings range from 0% (soil fully covered by mulch) to 100% (soil fully exposed/mulch deteriorated). Ratings were estimated in 1% increments up to 20% and in 5% increments above 20%. PLA = polylactic acid; PHA = polyhydroxyalkanoate.

Table 2. Mean number of weeds and dry weight (DW) (g·m⁻²) at early, mid-, and late season in the pepper field in Knoxville, TN, in 2017 and 2018. Bare ground plots were hand weeded.

Treatment	No. weeds (per m ²)	DW (g·m ⁻²)	No. weeds (per m ²)	DW (g·m ⁻²)	No. weeds (per m ²)	DW (g·m ⁻²)
2017						
	19 June		19 July		6 Sept	
Bare ground	88.5 a ^z	30.5 a	34.1 a	28.1 ab ^y	38.9 ab	25.4 abc
Bio360	1.3 d	0.3 d	13.4 b	28.1 c	37.1 b	29.1 c
Exp PLA/PHA	17.3 bc	6.3 bc	51.8 a	62.7 ab	68.2 ab	149.2 a
Naturecycle	16.0 b	6.0 b	43.6 a	51.6 abc	74.3 a	83.4 a
Organix	15.1 bc	6.4 ab	58.3 a	63.3 a	84.2 a	90.8 a
PE	3.0 bcd	1.4 bcd	34.1 a	23.7 ab	63.0 ab	66.7 ab
WeedGuardPlus	2.6 d	0.8 cd	6.5 b	10.1 bc	12.1 c	35.9 bc
White-on-black	3.5 cd	1.8 bcd	35.0 a	31.5 ab	47.5 ab	61.0 ab
P value	<0.0001	<0.0001	0.001	0.03	0.0006	0.02
2018						
	13 June		18 July		21 Aug	
Bare ground	11.2 de	0.5 b	41.9 cd	16.6 de	15.5 c	15.8 d
Bio360	23.7 bcd	1.9 b	83.7 bc	27.0 cd	165.3 a	210.5 ab
Exp PLA/PHA	144.2 a	16.5 a	309.5 a	506.5 a	179.6 a	701.2 a
Naturecycle	29.4 bc	3.4 ab	161.9 ab	116.1 abc	238.7 a	329.9 ab
Organix	18.1 bcd	2.2 b	159.7 ab	63.1 bc	172.7 a	275.3 ab
PE	14.7 cde	2.5 b	29.8 d	17.9 de	52.7 b	85.7 bc
WeedGuardPlus	1.7 e	0.2 b	15.5 d	2.9 e	16.8 c	95.7 cd
White-on-black	33.7 b	2.9 ab	174.0 ab	150.4 ab	162.3 a	435.2 ab
P value	<0.0001	0.02	<0.0001	<0.0001	<0.0001	<0.0001

^zTreatment means with the same letter within a given column are not significantly different (Fisher's least significant difference at $\alpha = 0.05$).

^yMean separation letters are taken from the transformed analysis; however, raw means are reported.

PLA = polylactic acid; PHA = polyhydroxyalkanoate; PE = polyethylene.

Table 3. Average counts of nutsedge plants (number of plants per m²) in plots by treatment for each weed rating date and for two of the PSE rating dates over the pepper-growing seasons in 2017 and 2018 in Knoxville, TN. Bare ground plots were hand weeded.

Treatment	Number of nutsedge plants per m ²							
	5 June 2017	19 June 2017	19 July 2017	6 Sept. 2017	1 June 2018 ^z	13 June 2018	18 July 2018	21 Aug. 2018
Bare ground	— ^z	10 abc ^y	4 c	30 bc	—	0 c	8 b	5 d
Bio360	2	1 c	13 bc	34 bc	6 cd	16 b	82 a	165 a
Exp PLA/PHA	5	17 a	51 a	67 ab	24 a	113 a	261 a	169 ab
Naturecycle	11	16 a	43 ab	72 a	17 ab	30 b	162 a	163 abc
Organix	11	14 ab	58 a	84 a	9 bcd	18 b	159 a	173 a
PE	3	3 abc	34 a	63 ab	6 cd	15 b	30 b	53 c
WeedGuardPlus	0	2 bc	1 c	6 c	0 d	0 c	11 b	10 d
White-on-black	6	4 abc	35 a	48 ab	13 bc	33 ab	174 a	99 bc
P value	0.19	0.04	<0.0001	0.0006	0.0007	<0.0001	<0.0001	<0.0001

^zCounts taken during PSE ratings, so data not available for bare ground treatment.

^yTreatment means with the same letter within a given column are not significantly different (Fisher's least significant difference at $\alpha = 0.05$).

PSE = percent soil exposure; PLA = polylactic acid; PHA = polyhydroxyalkanoate; PE = polyethylene.

Fig. 4. Number of healthy pepper plants in the data collection beds by a visual rating during the 2017 and 2018 pepper-growing seasons in Knoxville, TN. Treatment means with the same letter within a given date are not significantly different. Treatment means compared using Fisher's least significant difference at $\alpha = 0.05$. PLA = polylactic acid; PHA = polyhydroxyalkanoate.

treatments except Organix had significantly greater yields than Naturecycle. In 2018, bare ground and WGP plots had greater yields than all other treatments, except WOB (Table 4). Percent of unmarketable fruit by weight was greater in 2018 across all treatments compared with 2017 (Table 4).

There were no significant differences among treatments for extra large and jumbo fruit, and yields for these categories were very low over both years (data not shown). In 2017, Bio360 plots had a greater yield of large fruit than Naturecycle, Organix, and WOB plots. WGP had greater yields of small fruit compared with PLA/PHA, Naturecycle, and Organix (Table 5). WOB, WGP, bare ground, and PE plots had the greatest yields of choppers among treatments (for WOB this was mostly due to pancaking of fruit), whereas PLA/PHA and Naturecycle had the lowest yield of choppers (Table 5). In 2018, the trend with fruit sizes was different from in 2017, with all treatments having lower yields of large fruit. Bare ground, WOB, and WGP plots had the greatest yields across size categories, whereas PE had the lowest yields across categories (Table 5). Size classes by fruit number followed the same trends as size classes by weight (data not shown).

Total pepper harvest for individual harvest dates are shown by weight in Table 6.

Table 4. Total fruit yields and percent unmarketable by weight (tons per hectare) for all harvest dates for the 2017 and 2018 pepper-growing seasons in Knoxville, TN.

Treatment	Season total fruit yield by wt			
	2017 yield (t·ha ⁻¹)	2018 yield (t·ha ⁻¹)	% unmarketable 2017	% unmarketable 2018
Bare ground	35.8 ab ^z	24.4 a	5.7	19.3
Bio360	37.9 a	8.7 bc	8.9	28.2
Exp. PLA/PHA	27.7 ab	7.4 bc	10.5	30.3
Naturecycle	17.3 c	8.7 bc	13.0	23.1
Organix	26.8 bc	5.4 c	10.8	33.3
PE	33.8 ab	1.3 c	11.9	50.0
WeedGuardPlus	34.9 ab	22.1 a	9.7	31.6
White-on-black	33.7 ab	15.7 ab	13.3	31.4
P value	0.005	<0.0001	0.6296	0.5069

^zTreatment means with the same letter within a given column are not significantly different (Fisher's least significant difference at $\alpha = 0.05$).

PLA = polylactic acid; PHA = polyhydroxyalkanoate; PE = polyethylene.

Peak yields were in mid-August in both years (Table 6). Yields in 2017 were declining midseason as shown by the dip on 28 Aug. 2017 but rose again in Sept. 2017 (Table 6). This pattern was not seen in 2018 with yields lower for most treatments all season, and harvests ending 3 weeks sooner than in 2017 (Table 6).

Discussion

While the early season soil warming effect of PE mulch can increase yields of bell

pepper (e.g., Canul-Tun et al., 2017; Díaz-Pérez, 2010), in certain climates and conditions, black-colored mulches can decrease yields and possibly even degrade soil (Díaz-Pérez, 2010; Roberts and Anderson, 1994). There was not a clear difference in yield by color of mulch in 2017, but in 2018 all of the black-colored treatments had lower yields than the bare ground, WOB, and WGP treatments, with the lowest yields in Organix and PE. PE likely had the lowest yield in 2018 because it stayed the most intact and many of the plants failed to establish because

Table 5. Season total (all harvest dates) marketable pepper fruit by size classes by weight (tons per hectare) for the 2017 and 2018 pepper-growing seasons in Knoxville, TN.

Treatment	Marketable size classes—season total fruit (t-ha ⁻¹)							
	2017				2018			
	Small	Medium	Large	Choppers	Small	Medium	Large	Choppers
Bare ground	8.02 ab ^z	8.85	10.62 ab	5.07 ab	4.68 a	5.83 a	4.88 a	3.67 a
Bio360	7.02 abc	8.36	12.29 a	3.94 bc	1.83 bc	1.57 bcd	1.38 bc	1.44 bc
Exp. PLA/PHA	5.52 bc	7.82	7.17 abc	2.64 cd	1.47 bc	1.38 bcd	0.98 bc	1.24 cd
Naturecycle	4.77 c	4.01	3.74 c	1.77 d	1.18 bc	2.15 bcd	1.76 bc	1.06 cd
Organix	6.14 bc	5.69	6.19 bc	3.98 b	0.92 bc	1.01 cd	1.03 bc	0.58 cd
PE	6.89 abc	7.07	9.21 ab	4.67 ab	0.24 c	0.14 d	0.04 c	0.23 d
WeedGuardPlus	10.03 a	8.12	7.26 abc	5.25 ab	4.25 a	3.60 ab	3.59 ab	3.39 a
White-on-black	7.19 abc	7.49	6.12 bc	7.53 a	2.61 ab	2.29 abc	2.44 ab	2.80 ab
P value	0.04	0.06	0.04	<0.0001	0.0006	0.002	0.01	<0.0001

^zTreatment means with the same letter within a given column are not significantly different (Fisher's least significant difference at $\alpha = 0.05$).

PLA = polylactic acid; PHA = polyhydroxyalkanoate; PE = polyethylene.

Table 6. Total pepper harvest weight (tons per hectare) by harvest date over the 2017 and 2018 pepper-growing seasons in Knoxville, TN.

Treatment	Total harvest (t-ha ⁻¹) (avg per plot by date)															
	2017										2018					
	26 July	3 Aug.	10 Aug.	15 Aug.	22 Aug.	28 Aug.	5 Sept.	11 Sept.	19 Sept.	16 July	23 July	30 July	6 Aug.	13 Aug.	20 Aug.	27 Aug.
Bare ground	0.0	0.9 cd ^z	5.2 a	3.7 a	5.6	2.9	2.9	5.0	9.5	0.9	3.8 a	2.1	3.7 a	5.3 a	2.6 a	1.3 a
Bio360	0.8	2.6 ab	6.6 a	5.2 a	5.9	1.2	2.4	5.4	7.9	0.3	1.6 b	1.2	1.7 b	0.5 de	0.8 bc	0.3 bc
Exp. PLA/PHA	0.5	1.7 bc	5.5 a	1.4 bc	4.4	1.2	2.0	4.9	6.0	0.1	1.5 b	1.2	0.6 bc	1.1 cd	0.5 bc	0.2 bc
Naturecycle	0.2	0.4 d	1.7 b	0.7 c	1.7	1.0	2.2	3.0	6.5	0.7	1.3 b	0.7	0.6 bc	2.6 bc	0.6 bc	0.2 bc
Organix	0.7	3.0 ab	4.2 a	2.7 ab	4.7	0.9	1.7	4.0	5.8	0.4	1.1 b	0.9	0.2 cd	0.4 de	0.4 bc	0.2 bc
PE	1.2	3.7 a	6.2 a	3.2 a	5.2	1.6	1.8	4.0	6.9	0.1	0.1 c	0.2	0.0 d	0.2 e	0.2 c	0.0 c
WeedGuardPlus	0.1	1.8 abc	5.5 a	3.5 a	4.8	1.9	3.5	4.8	9.2	0.4	1.8 b	1.7	2.7 a	4.2 a	3.1 a	1.2 a
White-on-black	0.3	4.1 ab	11.1 a	4.6 a	4.8	0.5	1.7	2.0	4.7	0.8	2.3 b	1.9	1.3 b	2.7 ab	1.0 b	0.8 ab
P value	0.05	0.001	0.04	0.003	0.35	0.26	0.76	0.05	0.59	0.26	0.0001	0.06	<0.0001	<0.0001	0.0002	0.01

^zTreatment means with the same letter within a given column are not significantly different (Fisher's least significant difference at $\alpha = 0.05$).

PLA = polylactic acid; PHA = polyhydroxyalkanoate; PE = polyethylene.

of heat; this resulted in more mulch surface exposed to the sun than other treatments, contributing to greater soil temperatures. Díaz-Pérez (2010) observed that bell pepper fruit yield decreased with mean seasonal root zone temperatures (RZTs) above 27.5 °C, and that the optimal range of RZT for bell pepper fruit yield is 25 to 27.5 °C or less. In this study in both years, plants in the black-colored plots experienced more transplant shock than plants in bare ground, WOB, and WPG treatments. In 2017, most plants in the black-colored treatments recovered; however, in 2018, many did not recover, and yields suffered for all black-colored mulches. This trend was likely due to excessive RZT as described previously because soil temperatures at 10 cm for all black mulches were above this 27.5 °C threshold from 1 June to 25 June in 2018 (24 d), whereas in 2017, this threshold was only surpassed from 11 June to 19 June (8 d). Soil temperatures did rise above the 27.5 °C threshold again in July 2017, but it was after plants were well established. Similarly, Kader et al. (2017) found that soybean yield in a region experiencing very hot summer weather was greatest with a paper mulch compared with black PE mulch because of the root zone cooling effects. During the critical time when the pepper transplants were becoming established in June, average, minimum, and maximum air temperatures were greater in 2018 (24.0, 19.3, and 30.4 °C, respectively) than in 2017 (22.8, 17.7, and 28.9 °C, respectively). Roberts and Anderson (1994) report that pepper fruit set is

reduced when temperatures exceed 30 °C; and in the current study, air temperatures peaked above 30 °C for 52 d in 2017 (May–August) and 63 d in 2018 (May–August). Similarly, López-Marín et al. (2012) noted that regulating heat stress increased the marketable yield of bell pepper. Vos and Sumarni (1997) speculated that poor pepper plant establishment in their trials was likely due to excessive heat stress in some of their plastic-mulched plots. Mulch with the white surface facing up has been found to cool soil temperatures compared with clear- and black-colored mulches (e.g., Decoteau, 1989; Heißner et al., 2005), and we did find that WOB had greater yields for some harvest dates in 2018 than any of the black mulch treatments. Limpus et al. (2012) report that many growers in Australia are beginning to use WOB mulches year round to prevent seedling damage from hot spells. Decoteau (1989) concludes that mulch color selection for a particular crop may depend on the season and geographic area, which we found to be true in this experiment.

In the current study, we had to balance crop planting with the concurrent soil-monitoring component of this experiment (2015–18), forcing later transplanting than ideal for eastern Tennessee, which probably also contributed to heat stress in the black-colored mulch plots. Similarly, Hochmuth and Hochmuth (1994) demonstrated that pepper yields in Florida were greater with paper mulches than in PE in 1 year of their experiment, noting that lower yields on black

mulches that year may have been due to a later planting date and resulting heat stress.

Another reason for the greater yields in WGP and bare ground in 2018 was likely due to nutsedge pressure. The bare ground plots were hand weeded, which has been shown to be an effective, although very expensive, method to control nutsedge (Bangarwa et al., 2010). Morales-Payan et al. (1997) and Peerzada (2017) report that mechanical and cultural control of nutsedge through cultivation and other means usually is not economical or realistic, and an intensive, integrated approach is vital. There are reports that a stale seedbed method and/or repeated hand weeding or hoeing are effective in reducing nutsedge pressure (Wang et al., 2009). Recommended practices such as fumigation and stale seedbed/frequent tillage, however, were not available for use in this study because it would have interfered with the concurrent soil-monitoring experiment (Ghimire et al., 2018). Control with herbicides is difficult because most currently available herbicides do not kill the dormant tubers (Peerzada, 2017), and nutsedge control is only marginal (Bangarwa et al., 2009). Similarly, Adcock et al. (2008) found that preemergence herbicides did not reduce nutsedge penetration of PE mulch. Shading by an established crop such as cucurbits can reduce nutsedge tuber expansion (Johnson and Mullinix, 2008; Morales-Payan et al., 1997). We observed this shading effect as vigorous pumpkin vine growth suppressed, but did not eliminate, nutsedge in the 2015 to

2016 years of this experiment (Ghimire et al., 2018). This set the stage for explosive nutsedge growth and expansion in the 2017 and 2018 growing seasons with pepper as the crop, which provided much less canopy shade. Santos et al. (2007) observed that even low densities of yellow nutsedge can cause significant reductions in bell pepper yield, especially if the weed emerges early in the growing season, as it did in this experiment with nutsedge already penetrating mulch by the planting date. Similarly, Morales-Payan et al. (1997) observed that bell pepper yield decreased linearly with increasing purple nutsedge densities causing yield losses of up to 32% in bell pepper. Anzalone et al. (2010) observed that even though the PE mulch and BDMs were the same thickness, the nutsedge seemed to penetrate the BDM more easily. They speculate that this may be due to less resistance to perforation by the BDM or possibly weakness due to the beginning of biodegradation. This experiment seems to support both of these ideas, as nutsedge penetrated the PE mulch and BDMs within 1 week of laying both years, with greater numbers in 2018. It appears that for PLA/PHA and Naturecycle, less resistance may have been the cause, as they had the greatest counts of nutsedge by 1 June 2018. Alternatively, the lower counts of early season nutsedge in Bio360, Organix, and WOB seem to support the idea that BDMs are more easily penetrated by nutsedge than PE because of weakness and lower plasticity later in the season as they begin to biodegrade.

The WGP prevented emergence of nutsedge, whereas nutsedge penetrated all of the plastic mulches. Similar to Anzalone et al. (2010), we observed that the only nutsedge found in paper mulch beds emerged from planting holes or other tears or rips and that the weed did not penetrate intact paper mulch. One disadvantage of paper mulch is that it often breaks down quickly along the buried edges so that it is more easily damaged by wind than PE mulch or BDMs (Anzalone et al., 2010), and we did have some wind damage in these experiments; however, it was not extensive. If edge degradation does not happen until later in the season, often the crop is large enough to hold the mulch in place despite winds (Anzalone et al., 2010). Olsen and Gounder (2001) also found that tearing and wind damage were not significant problems in using paper mulch for pepper production in Australia. Coolong (2010) tested various paper mulches for summer squash production and concluded that, as with other types of mulch, the effectiveness of paper mulches depends on crop and environmental conditions.

This study shows that paper mulch performed better for pepper production than black plastic mulches (PE or BDM) in our area with hot summers and fields infested with nutsedge for midseason planting. WOB mulch was beneficial in this experiment for its cooling effect compared with the black mulches, resulting in better pepper plant health; however, it was not able to withstand

nutsedge penetration, which significantly lowered yield for this BDM treatment. As others have noted, hand weeding can successfully control nutsedge; however, this can be very expensive depending on labor costs in the area. Potential barriers to paper mulch use need to be addressed. The WGP paper mulch used in this project is commercially available; although shipping costs can be expensive and due to the weight of the mulch, the rolls are shorter (152 m/roll) so more rolls are needed to cover the same area compared with PE or BDMs (610–1219 m/roll). Once mulch-laying equipment was properly adjusted, time to lay the WGP creped paper mulch was the same as any of the other mulch treatments. We found that paper mulch stayed intact long enough to provide weed control during the critical period (first 4–6 weeks after planting), similar to the findings of Shogren and Hochmuth (2004) with watermelon in Florida. Others (Haapala et al., 2014) have pointed out issues with ripping, wind damage, and early breakdown along the buried edge of paper mulch. We experienced all of those issues in this experiment, but they were not severe and the advantages of the root zone cooling effect and the nutsedge control outweighed these effects. However, for an early-season crop, WGP might be less effective than black-colored mulches if soil warming is desired. In addition, in both years, there was no visible paper mulch left by the end of the season, so there were no disposal costs or mulch fragments remaining in the soil. In observations made every spring and fall after tillage, we did find some small fragments of BDMs remaining, which over time may affect yield in some way, but there have not been enough long-term studies with BDMs to make definitive conclusions. We found that for areas with hot summers and nutsedge weed pressure, paper mulch performed better than any of the plastic mulches tested. As others have noted (e.g., Kader et al., 2017), it is important for growers to assess their crop, season, climate, and weed community when choosing a mulch product.

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