Short-term Preemergence Herbicide Adsorption by Mulch Materials and Impacts on Weed Control

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SUMMARY. The objective of this research was to determine how mulch type affects adsorption and efficacy of commonly used preemergence herbicides in nurseries and landscapes. Nursery containers were filled with standard potting media and mulched with either pine bark (PB) mini-nuggets (mixed *Pinus* sp.), pine straw (PS; mixed *Pinus* sp.), or shredded eucalyptus hardwood (HW; *Eucalyptus* sp.) at a 2-inch depth. Herbicides including dimethenamid-P + pendimethalin (applied as a tank mix), prodiamine, and indaziflam were applied to mulched containers, watered in, and the mulch was subsequently removed 3 days later. Seeds of garden spurge (*Euphorbia hirta*), large crabgrass (*Digitaria sanguinalis*), and eclipta (*Eclipta prostrata*) were then seeded and used as bioassay species for dimethenamid-P + pendimethalin, prodiamine, and indaziflam, respectively. Chemical assays were also performed using a separate set of pots mulched with PB at 2 inches and treated with the same herbicides. Results from the bioassay experiment showed PS was the only mulch type that did not significantly decrease efficacy of any applied herbicide. Chemical assays showed only 34% of the applied dimethenamid-P reached the soil surface as evidenced by chemical assay, but more dimethenamid-P moved through PB than did pendimethalin (12%) or prodiamine (17%), which adsorbed more strongly. Overall results suggest preemergence herbicides will be strongly adsorbed to organic mulch. However, as mulch is typically more effective on weeds that germinate below the mulch layer, this does not automatically result in reduced efficacy from herbicide + mulch combinations, and the addition of a preemergence herbicide may be effective in reducing weed germination within or on top of the mulch layer.

Mulching is one of the most widely adopted and effective methods of weed control in landscape planting beds (Chalker-Scott, 2007; Marble et al., 2015a). Although mulch is an effective weed management tool, pre-emergence herbicides may be used in combination with mulch to reduce labor costs associated with hand weeding, repeated application of postemergence herbicides, or both

(Marble, 2015; Marble et al., 2015a, 2015b; Wilen and Elmore, 2007). In addition to weed control benefits, use of common mulch, such as PB or PS, has been shown to reduce runoff and leaching of preemergence herbicides, including pendimethalin, metolachlor, and isoxaben, by 35% to 74% in the landscape compared with application of these herbicides to bare soil

(Knight et al., 2001). Container nurseries also may use various mulch materials for weed control (Case et al., 2002). Addition of mulch as part of an overall integrated weed management program could reduce the number of herbicide applications needed, improve weed control and crop safety when using preemergence herbicides, and could potentially reduce runoff or leaching of preemergence herbicides (Bartley et al., 2017; Mathers and Ozkan, 2001; Wilson et al., 1996).

In general, wood products, PB, and other plant residues have a high sorption capacity for many herbicides (Brás et al., 1999; Huang et al., 2006). Herbicide sorption to organic mulch is dependent upon herbicide properties, namely solubility and soil adsorption coefficient [K_{oc} (Aslam et al., 2013; Senseman, 2007; Weber, 1990)]. In addition to herbicide properties, herbicide adsorption will be influenced by the chemical and physical composition of mulch or plant residues, which are dependent on material age or stage of decomposition, the origin of the material, and the particle size or surface area (Ahmad et al., 2001; Aslam et al., 2013; Benoit et al., 2008; Dao, 1991).

There have been few studies focusing on sorption of preemergence herbicides used in ornamentals with common landscape or nursery mulch materials. In field crops, increasing levels of plant residue on the soil surface in conservation tillage systems have been reported to cause reductions in herbicide efficacy due to herbicide adsorption (Buhler, 1992). Mulch or residue materials usually decrease efficacy by binding the herbicide and inhibiting it from reaching the soil surface or by increasing

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
1.0432	fl oz/oz	mL·g ⁻¹	0.9586
0.0929	ft ²	m ²	10.7639
3.7854	gal	L	0.2642
9.3540	gal/acre	L·ha ⁻¹	0.1069
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
6.4516	inch ²	cm ²	0.1550
1.1209	lb/acre	kg·ha ⁻¹	0.8922
0.0160	lb/ft ³	g·cm ⁻³	62.4274
0.5933	lb/yd ³	kg·m ⁻³	1.6856
28.3495	oz	g	0.0353
28,350	oz	mg	3.5274 × 10 ⁻⁵
1	ppm	mg·L ⁻¹	1
6.8948	psi	kPa	0.1450
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

microbial activity and thereby increasing the speed of herbicide degradation (Banks and Robinson, 1986; Chauhan and Abugho, 2012; Locke and Bryson, 1997). Banks and Robinson (1984) studied the effects of oryzalin applied to straw-covered and non-mulched soils. The amount of oryzalin reaching the soil surface was reduced in the presence of straw at the time of herbicide application, and the oryzalin concentration in the soil declined as the amount of straw increased. Similar results have been reported with pendimethalin and oxadiazon when applied to soils mulched with rice (*Oryza sativa*) residues (Chauhan and Abugho, 2012).

In contrast, Crutchfield et al. (1986) investigated the effects of metolachlor when applied to wheat (*Triticum* sp.) straw mulch and reported that although soil concentrations of metolachlor were significantly lower when applied in the presence of mulch, weed control increased with increasing mulch level due to the weed suppression ability of the mulch. In ornamental production, synergistic herbicide and mulch interactions have been reported, as mulch may act as a slow-release herbicide carrier, extending the longevity of weed control, or provide control of weeds when mulch alone or mulch depth is insufficient (Case et al., 2002; Mathers and Case, 2010; Saha et al., 2019). However, observed synergism with herbicides and mulch typically results when mulch is applied at an adequate depth, usually more than 2 inches (Marble, 2015). Herbicide degradation will occur more rapidly than mulch degradation, and after several months, the type and depth of mulch will be the most important factors in terms of weed suppression if sequential herbicide applications are not made (Bartley et al., 2017).

It has been established that significant herbicide adsorption can occur when applied to mulched soils, but impacts on efficacy may or may not occur depending on mulch depth and the weed species evaluated (Banks and Robinson, 1984; Chauhan and Abugho, 2012; Crutchfield et al., 1986). Most of the research on herbicide adsorption to mulch has focused on no-till situations that are not applicable in most nursery or landscape environments for several reasons. First, in container

ornamentals or landscapes, mulch is often not applied at recommended depths of 2 to 3 inches (Chalker-Scott, 2007). This commonly occurs in nurseries, as containers are completely filled with potting media, and depths of 2 to 3 inches may be cost prohibitive or difficult in large landscapes. As many common landscape and container weed species can emerge through mulch depths of 2 inches or more, herbicide adsorption could decrease control if depths of 2 inches or less are used (Richardson et al., 2008; Saha et al., 2019; Teasdale and Mohler, 2000). Second, mulch is often lost in container plants from blow over during weather events or moving containers during normal operations. Consequently, significant adsorption could lead to poor weed control if mulch were removed from containers. Most research on mulch and herbicide use in ornamentals has focused on long-term efficacy of various mulch-herbicide combinations (Bartley et al., 2017; Case et al., 2005; Mathers and Case, 2010; Saha et al., 2019). For landscapes and nursery scenarios, it is unknown how much herbicide is immediately adsorbed or intercepted by mulch or how efficacy would be affected if mulch levels were not sufficient for weed control or if mulch was lost soon after application. Therefore, the objective of this research was to assess adsorption of preemergence herbicides to mulches commonly used in nurseries and landscapes using short-term bioassay and chemical assay experiments conducted soon after herbicide application.

Materials and methods

CONTAINER BIOASSAY EXPERIMENTS. Research was conducted at the Mid-Florida Research and Education Center, Apopka, FL, in Summer 2018. Plastic nursery containers (5.5 inches width × 5.5 inches height with 1.7 L volume) were filled with a PB:peat substrate (Fafard52 growing mix; Sun Gro Horticulture, Agawam, MA) amended with 10 lb/yard³ 15N–3.9P–9.9K controlled-release fertilizer (Osmocote Plus; Everris, Geldermalsen, The Netherlands) based on the manufacturer's recommended medium rate for incorporation. PS (Pine Straw of Central Florida, Winter Garden, FL), PB mini-nuggets (Timberline Old Castle Lawn & Garden Inc., Atlanta, GA),

or shredded eucalyptus HW mulch (Florida Select Natural Eucalyptus Mulch; Scotts, Marysville, OH) were then applied at a depth of 2 inches on top of each container. Herbicides chosen for evaluation included indaziflam (Marengo 0.622 SC; Bayer Crop Science, Research Triangle Park, NC), prodiamine (Barricade 4 FL; Syngenta Crop Protection, Greensboro, NC), and dimethenamid-P + pendimethalin (Tower 6 EC + Pendulum 3.3 EC; BASF Corp., Research Triangle Park, NC). Herbicides were chosen because they are commonly used in both landscape beds and in nurseries and represent three commonly used herbicide mechanisms of action used in and around ornamental plants in Florida (Neal et al., 2017). These herbicides and mulch types also have been evaluated previously for weed efficacy, both when in combination and when used individually over a longer-term study (Saha et al., 2019). Indaziflam, prodiamine, and dimethenamid-P + pendimethalin were applied at labeled rates (0.04, 1.5, and 1.5 + 2.0 lb/acre, respectively) to mulched containers using a carbon dioxide backpack sprayer (Bellspray; R&D Sprayers, Opelousas, LA) calibrated to deliver 20 gal/acre using a flat-fan nozzle tip (8004; TeeJet Technologies, Wheaton, IL) at 30 psi on 6 June 2018 (run 1) and 12 July 2018 (run 2). Two separate groups of controls were maintained for comparison. First, a nonmulched herbicide control was included that was treated with aforementioned herbicides but was not mulched at the time of application. A nonmulched, nonherbicide-treated control was also maintained for comparison. Following treatment, all containers were placed on an outdoor nursery pad.

Although reports with indaziflam and prodiamine are lacking, downward leaching of up to 9 cm has been reported with pendimethalin and dimethenamid-P in PB substrates following 1-inch of irrigation applied daily for 7 d (Derr et al., 2015; Robertson and Derr, 2017; Simmons and Derr, 2007). Therefore in the present study, only 0.5 inch of irrigation was applied per day over only 3 d (1.5 inches total) with the aim of minimizing leaching in the potting substrate while also allowing for proper incorporation of herbicides

(required irrigation volumes of 0.25 to 0.5 inch) based on manufacturer recommendations for all four herbicides. Following irrigation and at 3 d after herbicide treatment, mulch was carefully removed from each pot using forceps so that only the herbicide reaching the substrate surface was available for weed control and the presence of mulch did not confound results. Following mulch removal, 20 seeds of either eclipta, large crabgrass, or garden spurge were surface sown to the previously mulched pots and used as bioassay species to assess herbicide adsorption to mulch. Eclipta was used for indaziflam, large crabgrass for proflam, and garden spurge for dimethenamid-P + pendimethalin. These weed species were chosen because they are problematic in nurseries and landscapes in Florida and have previously shown a high degree of sensitivity to the aforementioned herbicides (Neal et al., 2017; Saha et al., 2019). The experiment was a completely randomized design with six single pot replicates per herbicide and mulch combination and the nontreated, nonmulched control group. This resulted in five total treatments for each weed species, including each mulch type (HW, PB, or PS) with herbicide, a herbicide-only control, and the nonmulched, nontreated control.

Data collection included weed counts at 2 and 4 weeks after treatment (WAT). At 4 WAT, all weed species were cut at the soil line and shoot fresh weights were determined. All data were subjected to a mixed model analysis of variance (ANOVA) after meeting the assumptions of normality using SAS (version 9.4; SAS Institute, Cary, NC). Mulch types were fixed effects and the different experimental runs and replication were random effects. All data were subjected to a mixed model ANOVA after meeting the assumptions of normality using SAS (version 9.4). Mulch types were fixed effects and the different experimental runs and replication were random effects. Fisher's protected least significance difference test was used to compare means of experimental variables. All differences were considered significant at $P \leq 0.05$ and each weed species was analyzed separately.

CHEMICAL ASSAY EXPERIMENT. In addition to the bioassay described

previously, chemical assays were performed to estimate herbicide adsorption to PB mulch. PB mulch was chosen for these experiments because it is one of the most commonly used mulch materials used in both container nurseries and in landscapes in Florida. Round plastic nursery containers (10 inches diameter $\times$ 5 inches height) were filled with substrate and amendments as previously described. PB mulch was then applied at a depth of 2 inches on top of each container. A nonmulched control was also included for comparison of herbicide concentration in the substrate with and without mulch at the time of application. Commercially available liquid formulations of indaziflam, proflam, and dimethenamid-P + pendimethalin were applied as described previously, and pots were irrigated in the same manner as the bioassay experiment. Following treatment and 1.5 inches of irrigation, mulch was removed carefully with forceps without disturbing the underlying substrate as described previously.

Following mulch removal and irrigation, the substrate beneath the PB mulch was sampled to a depth of 1 inch from each container for herbicide quantification using a metal spatula. A total volume of 0.82 L of potting substrate was collected from each container but the PB mulch was not analyzed. Quantification of each herbicide in the substrate underneath mulch was determined using previously described methods [U.S. Environmental Protection Agency (USEPA), 2016, 2018a, 2018b]. Briefly, after collection, samples were placed in paper bags and stored in a walk-in cooler maintained at 4 °C until analysis. Before chemical analysis, substrate samples were transferred from the cooler and allowed to air dry at room temperature. The Soxhlet extraction procedure was used for herbicide extraction on substrate samples (USEPA, 2016). Samples were mixed with anhydrous sodium sulfate and extracted using acetone:hexane (1:1 by volume) as solvent in a Soxhlet extractor. Reverse-phase high-performance liquid chromatographic (RP/HPLC) and thermospray (TS) mass spectrometric (MS) conditions were used for the detection of the indaziflam. Sample extracts were analyzed by direct injection (100 μ L volume of sample)

onto a liquid chromatographic-TS interface. A gradient elution program was used on the liquid chromatograph to separate the compounds. Quantitative analysis was performed by TS/MS detection (USEPA, 2018b). For the detection of dimethenamid-P, pendimethalin, and proflam herbicides from the substrate extract, gas chromatography (GC)/MS was used. The sample extracts were injected into a GC equipped with a narrow-bore fused-silica capillary column. Identification of the target analyte (dimethenamid-P, pendimethalin, or proflam) was accomplished by comparing their mass spectra and retention times with the mass spectra and retention times of known standards. Quantification was accomplished by comparing the response of a major (quantitation) ion relative to an internal standard using calibration curves (USEPA, 2018a). All herbicide quantification data were converted to percent retention by PB mulch by using the formula $\{[(\text{nonmulched} - \text{mulched}) / \text{nonmulched}] \times 100\}$. The experiment was organized as a completely randomized design following treatment with three single pot replicates per treatment as described in the bioassay experiment. Data were arcsine square root transformed before analysis to meet the assumptions of ANOVA and subsequently analyzed as previously described. Untransformed data are reported to retain biological meaning.

MULCH PHYSICAL PROPERTY ANALYSIS. Physical analysis included particle size distribution, bulk density, and volumetric calculations to determine percentages of air, water, and solid in a given volume of mulch. Average mulch surface area was also estimated for mulch particles and on a volume basis. All analyses were determined in laboratory settings at the Mid-Florida Research and Education Center and were repeated in time using four replicates per mulch type for each experimental run. Mulch samples were spread into a single layer in the laboratory and allowed to air dry before all analysis.

Particle size distribution was determined by placing four 100-g samples of mulch through a series of U.S. standard soil sieves (WS Tyler, Mentor, OH) ranging from 50 mm to less than 2 mm. Sieves were stacked in descending order, placed in a mechanized sieve

shaker (model no. SS-15; Gilson Co., Lewis Center, OH) for 5 min, and then mulch in each size was weighed and recorded. Bulk density was determined by lightly packing mulch samples into a box (12 inches width $\times$ 12 inches width $\times$ 12 inches height). Materials were lightly packed by dropping a perforated metal plat (750 g weight) five times from a height of 2 inches above the mulch surface (Crown et al., 2013). After mulch was packed, dry weight was recorded. In bioassay experiments described previously, mulch was added based on volume but weight was estimated by multiplying bulk density by the volume of mulch in each container.

Volumetric calculations for air, water, and solid space for each mulch in a given volume were completed for each mulch on a percentage basis using previously described procedures with some modification (Akdeniz et al., 2011; Powrie, 2014; Simmons and Derr, 2007). Mulch materials were lightly packed inside 2.2-L containers and dry weights were recorded. Containers were then placed inside a water bath with a water level equal to the mulch level in the container. Each mulch-filled container was covered in plastic wrap and covered with a weighted plastic tray to prevent evaporation and mulch floating. Containers were allowed to saturate for 24 h so that all macropore (air space in between mulch particles) and micropore (water absorbed inside mulch particles) space was filled with water. After 24 h, containers were drained until all dripping ceased and water from each container was recorded (air space or macropore space). Containers were then weighed again to determine amount of water absorbed by mulch (water space or micropore space). Percent air in each container was calculated by dividing volume of water that dripped from the container by the container volume. Percent water was calculating by dividing the difference between mulch wet weight and mulch dry weight by the container volume. The remaining percentage represented the percentage of solid material in each container.

Mulch materials are generally composed of a wide range of particles with different sizes that change over time as materials degrade (Duryea et al., 1999). Therefore, average

surface area was estimated for both representative samples using weight and for individual particles. In both cases, mulch surface area was determined using ImageJ software (National Institutes of Health, Bethesda, MD) (Schneider et al., 2012). To determine surface area using mulch weight, a white corrugated plastic board was cut into a 1-m² square section and 100 g mulch samples were spread evenly into a single layer over the sheet, ensuring that no particles were overlapping. Photos were taken using a digital camera (model D3400; Nikon, Tokyo, Japan) at a height of 5 ft directly over the sheet using a custom-built frame so that all images were taken from the same height and location relative to the plastic board. Images were then analyzed in ImageJ using the threshold option. This gave a percentage of the plastic sheet (1 m²) covered with each 100-g sample of mulch. Surface area for 1 g of mulch was calculated by dividing surface area by 100. Average surface area for individual particles was accomplished using the soil-sieving method described previously. First, the percentage of each 100-g sample was determined for each sieve size as described previously. Percentages were then divided by 10, rounded to whole numbers, and then used to determine how many particles from each screen size to select for surface area determination. For example, if 32.4 g of PB was collected in the 12.5-mm sieve, three individual particles were randomly selected from that sieve. Particles that could not be positively identified as either HW, PB, or PS (e.g., very small particles) were excluded from analysis. Total surface area was determined using ImageJ and then divided by the number of individual particles in each image to calculate average surface area of an individual mulch particle. All physical property analyses were analyzed statistically as previously described.

Results and discussion

CONTAINER BIOASSAY EXPERIMENTS. Garden spurge counts at 2 WAT showed that HW was the only mulch material that significantly reduced dimethenamid-P + pendimethalin efficacy in relation to non-mulched pots (Table 1). At 4 WAT, similar results were observed, but at this evaluation timing, PS was the

only mulch material that did not significantly reduce weed counts in relation to the nonmulch pots. The combination of dimethenamid-P + pendimethalin provided similar control of garden spurge when it was applied to the nonmulched substrate and pots originally mulched with PS, with both treatments resulting in 100% control. Pots that were originally mulched with either HW or PB provided commercially acceptable control (96% control), but to a lower degree than was observed in non-mulched pots or pots originally mulched with PS.

Similar to results observed with garden spurge and dimethenamid-P + pendimethalin, PS was the only mulch material that did not significantly reduce efficacy of indaziflam at 2 WAT or 4 WAT based on eclipta counts. When indaziflam was applied to pots initially mulched with PB (88% reduction in counts) and PS (99% reduction in counts), eclipta counts was similar to that of non-mulched pots (100% reduction in counts), indicating that these two mulch types had no detrimental effect on indaziflam efficacy of eclipta (Table 1). Only 72% reduction in eclipta counts was observed in pots originally mulched with HW, which indicates that indaziflam was more tightly bound to this mulch, or was adsorbed to a greater degree with HW compared with PB or PS.

At 2 WAT, all mulch materials resulted in reduced efficacy of prodiamine based on large crabgrass counts. Large crabgrass counts ranged from 1.3 to 1.5 per pot, equivalent to a 55% to 61% reduction in based on the nontreated, non-mulched pots, whereas a 97% reduction was observed in pots that were treated with prodiamine but were not mulched. Large crabgrass fresh weight data showed that PB (57% control) was the only mulch type that caused a significant reduction in prodiamine efficacy. Prodiamine provided a similar reduction in large crabgrass fresh weights when pots were originally mulched with HW or PS (84%) and when no mulch was present (100%). Although a high degree of large crabgrass control was observed, it should be noted that germination was less than expected. Although spotted spurge and eclipta germination averaged 55% and 87% in

Table 1. Weed counts and shoot weights of three weed species following application of preemergence herbicides to mulched pots and subsequent mulch removal following 1.5 inches of overhead irrigation. Percent reductions for weed counts and shoot fresh weight relative to nontreated, nonmulched pots are shown parenthetically by each mean.

Mulch type ^z	Garden spurge			Eclipta			Large crabgrass		
	Dimethenamid-P + pendimethalin			Indaziflam			Prodiamine		
	Weeds (no./pot)			Weeds (no./pot)			Weeds (no./pot)		
	2 WAT ^y	4 WAT	Shoot fresh wt (g) ^x	2 WAT	4 WAT	Shoot fresh wt (g)	2 WAT	4 WAT	Shoot fresh wt (g)
Hardwood	2.4 (76%) a ^w	2.8 (75%) a	0.3 (96%) a	6.7 (60%) a	6.7 (62%) a	1.9 (72%) a	1.5 (55%) a	1.6 (57%) a	0.7 (84%) ab
Pine bark	1.1 (89%) ab	1.4 (88%) b	0.3 (96%) a	3.5 (78%) b	3.1 (82%) b	0.8 (88%) b	1.4 (58%) a	1.5 (60%) a	1.9 (57%) a
Pine straw	0.0 (100%) b	0.1 (99%) c	0.0 (100%) b	1.4 (91%) c	0.8 (96%) c	0.1 (99%) b	1.3 (61%) a	0.8 (78%) ab	0.7 (84%) ab
None ^v	0.0 (100%) b	0.0 (100%) c	0.0 (100%) b	0.1 (99%) c	0.0 (100%) c	0.0 (100%) b	0.1 (97%) b	0.0 (100%) b	0.0 (100%) b
Nontreated ^u	10.1	11.3	7.9	16.1	17.4	6.9	3.3	3.7	4.9

^zMulch applied at a 2-inch depth was removed from containers before sowing weed seeds at 3 d following preemergence herbicide applications and 1.5 inches of cumulative overhead irrigation; 1 inch = 2.54 cm.

^yWAT = weeks after treatment. Weed counts in nontreated, nonmulched pots were 10.1 and 11.3 for garden spurge, 16.1 and 17.7 for eclipta, and 3.3 and 3.7 for large crabgrass at 2 and 4 WAT, respectively.

^xShoot fresh weight collected at 4 WAT. Mean shoot weights in nontreated, nonmulched pots were 7.9, 6.9, and 4.4 g for garden spurge, eclipta, and crabgrass, respectively; 1 g = 0.0353 oz.

^wMeans within a column followed by the same letter are not significantly different according to Fisher's protected least significant difference ($P < 0.05$).

^vNone refers to pots that were treated with herbicide but contained no mulch at the time of application.

^uNontreated refers to pots that contained no mulch and were not treated with herbicide, and were used for comparison but not included in analysis.

nontreated controls, respectively, large crabgrass germination was low and only 19% germination was observed in nonmulched, nontreated controls (Table 1). However, as germination was close to 20% and was consistent at this level in nontreated controls, it is likely these data still provide a suitable demonstration of prodiamine adsorption in a nursery or landscape environment. However, it is possible that large crabgrass control would be lower than reported here if higher weed pressure was present.

CHEMICAL ASSAY EXPERIMENTS. PB retained pendimethalin (88%) and prodiamine (83%) to a greater degree than dimethenamid-P (66%) as evidenced by chemical assays of the substrate beneath the mulch layer (Table 2). Only 12% and 17% of the applied pendimethalin and prodiamine reached the underlying substrate surface, whereas 34% of the applied dimethenamid-P was recovered in the substrate. This result was similar to previous findings following a pendimethalin application to sugarcane (*Saccharum* sp.) mulch residue (Selim et al., 2003). Selim et al. (2003) reported up to a 50% reduction in pendimethalin concentration in soils in which sugarcane residue was left on the soil surface following harvest. Similar results have been reported with switchgrass (*Panicum virgatum*) residues (Mersie et al., 2006). More than 80% retention was observed in our study, likely due to the higher mulch level present (2 inches). Both pendimethalin and prodiamine have comparatively low solubility values and high adsorption coefficients (K_{oc}), and are not prone to leaching and are generally tightly bound to organic particles, such as a PB mulch (Table 2) (Senseman, 2007; USEPA, 2010). Conversely, dimethenamid-P is characterized as having a higher likelihood of leaching due to greater solubility and lower K_{oc} . Pendimethalin and prodiamine leaching have been shown to be minimal in PB substrates (Simmons and Derr, 2007; Stewart et al., 2019). However, a greater void space in a mulch material compared with the previous studies with PB growing substrate is likely to cause more downward movement (Simmons and Derr, 2007), leading to a recovery of 12%

to 17% through the mulch layer. At 77% retention by PB, indaziflam was similar to the other herbicides evaluated. Indaziflam movement through a PB mulch or PB substrate have not been previously reported, but leaching in a fine Candler sand soil in Florida has been reported to be limited under simulated high rainfall due to the relatively low solubility characteristics of indaziflam (Jhala and Singh, 2012).

PHYSICAL PROPERTY ANALYSIS. Particle size analysis showed that PS was mostly composed of particles larger than 50 mm (57.7%), whereas PB was mostly composed of particles ranging from 25 to 6.3 mm (Table 3). HW mulch tended to have a greater percentage of smaller particles compared with PB or PS with most particles ranging from 6.3 mm to less than 2 mm. PB had the highest bulk density of any mulch ($0.18 \text{ g}\cdot\text{cm}^{-3}$) followed by HW ($0.09 \text{ g}\cdot\text{cm}^{-3}$) and PS ($0.04 \text{ g}\cdot\text{cm}^{-3}$). Surface area calculations showed that although individual PB particles had a larger surface area for individual particles, a higher bulk density resulted in a lower surface area value for PB compared with HW or PS when examining surface

area on a mulch weight basis (Table 4). Void space within the three mulch types showed that a layer of PS contained a higher percentage of air space (85%) compared with HW (67%) or PB (58%). Conversely, PS had the least amount of solid material (i.e., mulch) (9%) compared with HW (17%) or PB (30%). These data indicate that in a given mulch layer, PS contained the most air or void space, followed by HW and PB. PS (6%) also absorbed less water than PB, whereas HW absorbed the most.

Similar to previous findings (Johnson, 1997; Marble et al., 2011), herbicides evaluated in these experiments provided a high level of control of each bioassay weed species when applied to the substrate surface when no mulch was present at the time of application. When mulch was present during the application, results differed by herbicide and mulch material. PS was the only mulch material in which weed counts and fresh weights of the target weed species were consistently similar to the non-mulched control group. The only exception was with proflam and large crabgrass at 2 WAT, when large

crabgrass counts were significantly higher in all pots that initially contained mulch. PS did not cause any reductions in efficacy based on counts or shoot fresh weights at 4 WAT for any of the three weed and herbicide combinations evaluated. This indicates that the herbicides evaluated in this study likely adsorbed less to PS compared with HW or PB mulch.

Less interception by PS is likely attributable to a higher percentage of large particles compared with PB or HW and greater air or void space. Both HW and PB contained more small particles than did PS and had greater bulk densities, resulting in less solid mulch particles occupying the 2-inch mulch layer in containers. A higher percentage of smaller particles present in HW and PB also provides more adsorption sites for herbicides, similar to previous reports with PB and other particulate organic matter (Benoit et al., 2008; Brás et al., 1999). Although the surface area of individual particles for HW and PS were similar, a 2-inch layer of HW would have more than twice the weight of a 2-inch layer of PS and contain 67% air or void space compared with 85% air space for PS (Table 4).

Previous research has also shown that herbicide adsorption can be influenced by chemical composition. In wood- or plant-derived mulch materials, increased adsorption is associated with increased lignin content, whereas a higher percentage of cellulose often limits herbicide sorption (Benoit et al., 2008; Dao, 1991; Riggle and Penner, 1992). Reports of lignin and cellulose concentrations of HW, PB, and PS mulch show that generally, PS and HW have similar lignin (30% to 38%) concentrations, that is, less than PB (45%) (Table 5). Lignin has typically been shown to have high adsorption potential, thus it would be expected for PB would have a greater tendency to bind herbicides compared with HW or PS (Dao, 1991). Higher cellulose concentrations are also negatively correlated with herbicide adsorption, and both PS and HW also had higher cellulose concentration compared with PB. Although lignin and cellulose concentrations were generally similar between HW and PS, lower bulk density and consequently greater air space and larger particle sizes associated with PS likely contributed

Table 2. Retention of preemergence herbicides in 2 inches (5.08 cm) of pine bark mulch following 1.5-inches (3.81 cm) of irrigation.

Herbicide	Solubility ($\text{mg}\cdot\text{L}^{-1}$) ^z	K_{oc} ($\text{mL}\cdot\text{g}^{-1}$) ^y	Retention (%) ^x
Dimethenamid-P	1174 ^y	55–125 ^u	66 b ^w
Indaziflam	4.4	496	77 ab
Pendimethalin	0.275	17,200	88 a
Proflam	0.013	13,000	83 a

^zSolubility values were derived from Senseman (2007) and U.S. Environmental Protection Agency (2010). Mean solubility values are given as solubility will be variable depending on temperature, pH, and other factors; $1 \text{ mg}\cdot\text{L}^{-1} = 1 \text{ ppm}$.

^y K_{oc} = soil adsorption coefficient. Values were derived from Senseman (2007) and U.S. Environmental Protection Agency (2010). Mean K_{oc} are given as adsorption and will be variable based on soil characteristics; $1 \text{ mL}\cdot\text{g}^{-1} = 0.9586 \text{ fl oz/oz}$.

^xMean percentage of herbicide retained in mulch layer by comparing herbicide concentrations in soil from nonmulched pots with herbicide concentrations in soil from mulched pots. Dimethenamid-P, indaziflam, pendimethalin, and proflam were applied at rates of 1.5, 0.04, 2.0, and 1.5 lb/acre or 8.5, 0.25, 11.2, and 8.5 mg/pot, respectively; $1 \text{ lb/acre} = 1.1209 \text{ kg}\cdot\text{ha}^{-1}$, $1 \text{ mg} = 3.5272 \times 10^{-5} \text{ oz}$.

^wMeans followed by the same letter are not significantly different according to Fisher's protected least significant difference ($P < 0.05$).

Table 3. Particle size analysis of hardwood, pine bark, and pine straw mulch.

Mulch type	U.S. Standard soil sieve size (mm) ^z							
	50	25	19	12.5	6.3	3.35	2	<2
	Mean retention by wt (%)							
Hard wood	0.0 b ^y	1.6 b	3.5 b	10.6 b	38.9 a	18.5 a	8.8 a	17.1 a
Pine bark	0.0 b	15.7 a	23.2 a	28.1 a	26.8 b	4.9 b	0.4 b	0.6 b
Pine straw	57.7 a	2.0 b	0.7 b	2.3 c	4.4 c	8.0 b	12.3 a	12.6 a

^zMulch was air-dried until reaching a constant weight and then four 100-g (3.53 oz) samples were passed through sieves in descending order; $1 \text{ mm} = 0.0394 \text{ inch}$.

^yMeans followed by the same letter within each sieve size are not significantly different according to Fisher's protected least significant difference ($P < 0.05$).

Table 4. Mean bulk density, surface area, and volumetric calculations for hard wood, pine bark, and pine straw mulch.

	Particle density ^z		Surface area (cm ²) ^y		Void space (%) ^x		
	Bulk density (g·cm ⁻³) ^z	Mulch wt in container (g) ^z	by wt (1 g)	by particle	Air	Solid	Water
Hardwood	0.09 b ^w	88.6 b	27.6 a	3.0 b	67 b	17 b	16 a
Pine bark	0.18 a	179.9 a	6.8 b	9.9 a	58 c	30 a	12 b
Pine straw	0.04 c	36.3 c	26.4 a	3.1 b	85 a	9 c	6 c

^zBulk density was calculated by weighing air-dried samples in a container with a known volume. Mulch weight in containers shows the average weight of a 2-inch (5.08 cm) layer of mulch in 1.7-L (0.45 gal) nursery containers used in bioassay experiments; 1 g·cm⁻³ = 62.4274 lb/ft³, 1 g = 0.0353 oz.

^yAverage mulch surface area was calculated using mulch weight and individual mulch particles using ImageJ software (Schneider et al., 2012); 1 cm² = 0.1550 inch².

^xVoid space shows average percentage of air, water, and solid in a given volume of mulch using a modified volume of voids calculation (Akdeniz et al., 2011; Simmons and Derr, 2007).

^wMeans within a column followed by the same letter are not significantly different according to Fisher's protected least significant difference ($P < 0.05$).

Table 5. Lignin, cellulose, and hemicellulose concentration of hard wood, pine bark, and pine straw mulch.

	Lignin	Cellulose Composition (%)	Hemicellulose
Hardwood ^z	30	48	22
Pine bark ^y	45	25	15
Pine straw ^x	38	43	22

^zDerived from average of listed values (Pereira et al., 2013).

^yDerived from average of listed values (Valentin et al., 2010).

^xDerived from average of listed values (Howard, 1973).

to less adsorption with this mulch. These results would agree with previous reports by Benoit et al. (2008), in that herbicide adsorption cannot be predicted based on chemical properties only, but that physical properties also play a significant role.

Results from these studies demonstrate commonly used preemergence herbicides in landscapes or nurseries are bound in organic mulch materials. Only 10% to 30% of the herbicide that was applied reached the substrate surface, at least initially following only ≈ 1.5 inches of irrigation over a short period, which is similar to previous findings (Banks and Robinson, 1982; Crutchfield et al., 1986; Dao, 1991). Although it is possible that herbicides leached downward beneath the 1-inch depth used for chemical analysis, this would be unlikely given that these herbicides are generally adsorbed tightly to PB substrates (Stewart et al., 2019). Only 1.5 inches of irrigation was applied over a short 3-d period in this study, and none of the evaluated herbicides would be expected to leach deeper than based on previous reports (Derr et al., 2015; Jhala and Singh, 2012).

Herbicides generally tend to adsorb more tightly to mulch materials

or soils with higher organic matter with up to five times greater adsorption being reported in mulches compared with field soils in some studies (Hodges and Talbert, 1990). Most previous research on herbicide movement or adsorption by mulch has been conducted in agronomic crops with lower levels of plant residue and with herbicides with higher solubility and K_{oc} than were evaluated in this experiment. Even among herbicides that would have a greater tendency to move through a mulch material, high levels are usually retained in the mulch or residue. For example, up to 60% of applied metribuzin was intercepted by a straw mulch (Banks and Robinson, 1982), whereas 80% of metolachlor was intercepted by wheat straw immediately after application (Crutchfield et al., 1986). Metribuzin has a K_{oc} of 60 mL·g⁻¹ and metolachlor of 200 mL·g⁻¹, which would be similar to dimethenamid-P (55 to 125 mL·g⁻¹) but significantly less than any other herbicides evaluated in this study (Table 2) (Senseman, 2007). These previous reports with metribuzin and metolachlor are in agreement with chemical assay data reported here in which 66% of applied dimethenamid-P was recovered under PB.

Although adsorption absorption to mulch is a rapid process, desorption is typically a slow process occurring over weeks or months depending on mulch degradation, herbicide half-life and adsorption coefficients, and environmental factors, including rainfall and irrigation (Aslam et al., 2013; Hodges and Talbert, 1990; Huang et al., 2006; Selim and Zhu, 2005). As most herbicide labels indicate that 0.25 to 0.5 inch of irrigation is needed to water in herbicides following application, it is possible additional irrigation will be needed with some preemergence herbicides applied to mulched nursery containers or landscape beds. Previous studies have reported that increased irrigation or rainfall may not result in significantly greater weed control or herbicide concentrations below mulch materials with herbicides with low solubility, such as pendimethalin (Banks and Robinson, 1982; Saha et al., 2019). Conversely, higher irrigation is likely to cause greater mobility and downward leaching of more water-soluble herbicides such as atrazine, which may also influence efficacy (Bauman and Ross, 1983; Ghadiri et al., 1984).

It is also important to note that these studies were conducted on commercially available mulch materials, and although the mulch was used immediately after procuring, the exact age of the material after harvesting was unknown. As herbicides degrade in a landscape or nursery environment, particle sizes will change, as will chemical composition (Duryea et al., 1999). Increased adsorption has been noted in plant residues and wood-derived mulches, thus additional research may be needed to determine the influence of aged mulch on herbicide efficacy over time (Aslam et al., 2013; Dao, 1991). Although only a small portion of the total herbicide applied reached the substrate surface in mulched containers, in most instances commercially acceptable (>80%) weed control was observed over the 4-week evaluation period even though mulch was removed and was not available to aid in weed suppression. Determining dose response relationships of each of these three weed species with the three different herbicidal products was beyond the scope of this experiment, but it is evident that these herbicides are relatively active on these weeds at low rates. It is unknown, however, how efficacy would be affected over

a longer period and or if seeds were sown on multiple dates.

Although these data show a high degree of herbicide binding to mulch, use of preemergence herbicides on mulched containers or landscape beds could still offer significant advantages. In many cases, weed germination and growth significantly increase when seeds are placed on top of mulch compared with seeds below mulch (Richardson et al., 2008; Saha et al., 2019). Therefore, an herbicide that is retained in the mulch layer may be available to prevent growth of weed seeds deposited on top of the mulch layer. Weed control from these different herbicide + mulch combinations (when mulch was left on the substrate surface) was not determined in the current study, but these combinations have been shown to provide season-long weed control in previous studies (Bartley et al., 2017; Saha et al., 2019; Somireddy, 2012). Similarly, in studies with crop residues, satisfactory weed control has often been reported even in cases in which most of the herbicide was intercepted by surface residue (Crutchfield et al., 1986; Ghadiri et al., 1984). This is primarily because weed control usually increases as mulch depth increases, regardless of weed seed placement due to the inhibitory effects of mulch on weed germination and growth (Crutchfield et al., 1986; Chalker-Scott, 2007; Ghadiri et al., 1984; Marble et al., 2015a, 2015b). Although these data show that PS may adsorb less herbicide than PB or HW, more data are needed to evaluate long-term control with these combinations in a variety of environments. Future research also should determine if herbicide application volume has any influence on mulch interception, and what role herbicide formulation/application method (granular vs. spray-applied) has on efficacy, movement, and activation. Cost, aesthetics, availability, durability, and consumer acceptance also should be considered when evaluating mulch either with or without the use of pre-emergence herbicides.

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