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Article

Preemergence Herbicides and Mulches for Cutting Propagation—Impact on Rooting, Growth after Transplant, and Weed Control

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Abstract: Weed control in cutting propagation is limited to manual hand weeding, which is time-consuming and labor-intensive. Preemergence herbicides and mulches may be viable weed control methods for cutting propagation, but crop safety and weed control efficacy must be better understood. Four preemergence herbicides (indaziflam, isoxaben, isoxaben + dithiopyr, and oxyfluorfen + oxadiazon) and two mulches (pine pellets and rice hulls) were assessed in cutting propagation for their impact on rooting and subsequent liner growth (butterfly bush [*Buddleja davidii* Franch.] and crape myrtle [*Lagerstroemia indica* L.]) and control of four common weed species. Butterfly bush cuttings had lower rooting percentage and root dry weight with isoxaben and isoxaben + dithiopyr, but no damage was observed for all other treatments during propagation or after transplant. Crape myrtle cutting root development and liner growth were statistically similar for all treatments compared to the non-treated control. Isoxaben, isoxaben + dithiopyr, oxyfluorfen + oxadiazon, and pine pellets provided excellent control (87 to 100%) of all four weed species tested. Overall, several preemergence herbicides and mulches were safe for use in cutting propagation and effective weed control varied by product and weed species.

Keywords: nursery crops; pine pellets; rice hulls

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1. Introduction

Weeds are a major problem in container nursery production and weed infestation issues commonly materialize during propagation. Most woody shrub species and many tree species are propagated by sticking cuttings in small-diameter containers then placing them under intermittent mist in greenhouses or outdoors under shade structures. Due to the smaller container sizes used during propagation, there is more competition for resources such as light, nutrients, and space among crop and weed species. Weed control in propagation is a problem currently addressed by manually removing weeds with hand weeding. Use of herbicides to control weeds during propagation would be beneficial; however, limited information is available on how herbicide affects rooting and subsequent root growth of woody rooted cuttings [1]. There are a very limited number of herbicides that are available for use in the ornamental plant industry [2]. Furthermore, many of the preemergence herbicides labeled for use in nursery crops contain dinitroanilines (DNAs) which inhibit root growth. As a result, hand weeding is commonly used for controlling weeds in propagation, but it is time-consuming and labor-intensive. The labor cost for hand weeding in container nurseries can total USD 9000 per hectare and can be up to 30 times more expensive than herbicide use, while an estimated overall economic loss of over USD 17,000 per hectare can be associated with weed infestations in nursery crops from several hundred to several thousand dollars per acre [2–4]. Additionally, there has been a decrease in the availability of the agricultural labor supply [5].

Although some preemergence herbicides can be injurious to sensitive crops and may hinder root development, certain products may be safe to use during propagation. Root-inhibiting herbicides such as oryzalin, pendimethalin, and trifluralin should be avoided in cutting propagation due to reports of reduced rooting and root damage to several ornamental crop species [6–9]. Non-root-inhibiting herbicides can be much safer to use during cutting propagation since their mode of action does not target root development processes. Oxadiazon is a preemergence herbicide that inhibits protoporphyrinogen oxidase formation which affects shoot growth and development. Since oxadiazon has no activity on root growth, it is commonly used on newly transplanted nursery stock. Additionally, multiple studies have demonstrated oxadiazon to be safe in cutting propagation on numerous crop species [6,7,10–13]. The combination of oxadiazon + oxyfluorfen has also been shown to be safe in cutting propagation of a limited number of ornamental crop species [6,13]. Isoxaben and indaziflam are preemergence herbicides widely used in nursery crops and both function by inhibiting cellulose synthesis which can affect root and shoot growth, but preliminary reports suggest isoxaben [10,13] and indaziflam [13,14] may be safe in cutting propagation. Nevertheless, further research is needed to test these active ingredients on additional crop species in cutting propagation.

Although cuttings may produce comparative root systems when using preemergence herbicides, subsequent growth after transplant should be monitored to identify any potential negative residual effects. Davies and Duray [7] reported that several herbicides had no negative effects on rooting during cutting propagation or growth after transplant of Asian jasmine (*Trachelospermum asiaticum* L.); Burford holly (*Ilex cornuta* Lindl. & Paxton 'Burfordii') and Lantana (*Lantana camara* L. 'New Gold'). Cochran et al. [10] demonstrated that *Loropetalum chinense* 'Ruby' cuttings treated with oxadiazon and isoxaben had similar root development after propagation, and similar root and shoot growth after transplant compared to non-treated cuttings. Due to this limited knowledge base on crop development after transplant, additional evaluations are necessary to screen different crop species and herbicide active ingredients.

Preemergence herbicides may effectively control weeds in the propagation environment, but no preemergence herbicides are labeled for use in propagation and nursery growers remain reluctant to use these products due to the safety issue on rooting [6,11]. Mulches are widely used for controlling weeds in nursery containers with high success, but they have not been widely evaluated in the propagation environment [15]. Rice hulls can provide excellent weed control for several weed species when applied at 1.3 to 2.5 cm depth in nursery container production [16,17]. In cutting propagation, the high moisture environment and frequent mist may negate the hydrophobic properties of rice hulls and can reduce weed control efficacy but other mulch materials such as pine pellets can maintain excellent weed control efficacy in the propagation environment [15]. Regardless of the mulch material used during propagation, growers need to be assured that subsequent liner growth will not be negatively impacted.

Understanding the short- and long-term effects of preemergence herbicides and mulches in cutting propagation would allow growers to make more informed choices when selecting an effective and safe weed management strategy. The objective of this study was to determine the effect of preemergence herbicides and mulches on rooting of cuttings, growth after transplant, and weed control efficacy.

2. Materials and Methods

Stem cutting root development and the growth of rooted cuttings after transplant were evaluated for two crop species treated with four preemergence herbicides and two mulches (Table 1). Weed control efficacy was evaluated for four common weed species of nursery crops. All trials were conducted at the Tennessee State University, Otis L. Floyd Nursery Research Center in McMinnville, TN (35.7102174° N, 85.7904774° W).

Table 1. Preemergence herbicides and mulches evaluated for cutting propagation, post-transplant growth, and weed control efficacy.

Product Type	Product	Active Ingredient(s)	Application Rate	Manufacturer Info
Non-treated control	n/a	n/a	n/a	n/a
Preemergence Herbicide	Gallery SC	45.45% isoxaben	1169 mL/ha	Corteva Agriscience LLC, Indianapolis, IN, USA
	Regal O-O	2% oxyfluorfen + 1% oxadiazon	112 kg/ha	Regal Chemical Company, Alpharetta, GA, USA
	Fortress	0.50% isoxaben + 0.25% dithiopyr	168 kg/ha	OHP, Inc., Bluffton, SC, USA
	Marengo G	0.0224% indaziflam	112 kg/ha	Bayer Environmental Science, Cary, NC, USA
Mulch	Rice hulls	n/a	1.3 cm	Riceland Foods, Inc., Stuttgart, AR, USA
	Pine pellets	n/a	1.3 cm	Tractor Supply Company, Brentwood, IN, USA

2.1. Propagation Trial

Terminal and sub-terminal 7.6–10.2 cm stem cuttings of two crop species (butterfly bush [*Buddleja davidii* Franch. 'Nanho Blue'] and crape myrtle [*Lagerstroemia indica* L. 'Catawba']) were collected from container-grown stock plants in April 2020. All cuttings received a 3 s basal quick dip in rooting hormone (500 ppm napthaleneacetic acid [NAA] + 1000 ppm indole-3-butyric acid [IBA] [Dip'N Grow; Clackamas, OR, USA]), and a single cutting was inserted into each 6.3 cm diameter square container (SVD250; T.O. Plastics, Clearwater, MN, USA) filled with a 100% pine bark substrate amended with controlled release fertilizer (CRF) (3.6 kg/m^3; Nutricote® Total 13N-4.8P-9K [100 d]; Florikan E.S.A. LLC, Sarasota, FL, USA), Micromax (0.6 kg/m^3; ICL Fertilizers, Dublin, OH, USA), and AquaGro 2000G (0.3 kg/m^3; Aquatrols, Paulsboro, NJ, USA). One day prior to sticking cuttings, preemergence herbicides and mulches (1.3 cm depth) were applied to containers, irrigated with 0.6 cm of water then placed back under intermittent mist. Sprayable herbicide was applied with a CO_2 sprayer fitted with a flat spray nozzle (TP8003VS; TeeJet Technologies, Wheaton, IL, USA) calibrated to deliver 280 L ha^{-1} at 207 kpa and granular herbicides were applied using a handheld shaker. Containers (25 replicates per treatment) were completely randomized (within species) and placed in a shade structure (50% shade cloth) under intermittent mist (VibroNet with blue nozzle; Netafim USA, Fresno, CA, USA) applied for 10 s every 8 min from 6:00 am to 9:00 pm. All containers were hand weeded throughout the study to eliminate weed competition effects. After sufficient rooting had occurred (based on the non-treated control), cuttings (less 8 from each treatment per species) were harvested for data collection which included rooting percentage ($\% = \frac{\textbf{number of rooted cuttings}}{\textbf{total number of cuttings}} \times 100$), shoot dry weight, root dry weight, and digital root analysis (total root length and root volume) using WinRhizo software (Reagent Instruments Inc., Quebec City, QC, Canada).

2.2. Transplant Trial

After rooting, 8 cuttings (8 replications per treatment per species) were randomly selected and transplanted [butterfly bush (8 June) and crape myrtle (29 June)] to a 2.4 L nursery container (trade gallon, 300S; Nursery Supplies Inc., Chambersburg, PA, USA) filled with a 100% pine bark substrate amended with CRF (4.5 kg/m^3; Nutricote® Total 13N-4.8P-9K), Micromax (0.9 kg/m^3), and dolomitic lime (3 kg/m^3), then placed on a greenhouse table and irrigated daily. Shoot growth (height and width), leaf greenness (SPAD-502 Plus; Konica Minolta, Ramsey, NJ, USA), substrate pH, and electrical conductivity were recorded monthly for 2 (butterfly bush) or 3 months (crape myrtle) after transplant (MAT). At termination, all plants were harvested to record shoot and root dry weight.

2.3. Weed Efficacy Trial

Weed seed germination assays were conducted to determine efficacy of the preemergence herbicides and mulches (Table 1) under propagation conditions. Weed species included bittercress (*Cardamine hirsuta* L.), crabgrass (*Digitaria sanguinalis* L.), creeping woodsorrel (*Oxalis corniculata* L.), and mulberry weed (*Fatoua villosa* [Thunb.] Nakai). Square containers (6.3 cm) were filled with a pine bark substrate (as previously described) and a separate set of containers was used for each species. Mulches and herbicides were applied (as previously described in Propagation Trial) and the following day 20 (creeping woodsorrel and mulberry weed) or 25 (bittercress and crabgrass) seeds were surface-sown in each container. Containers (8 replicates per treatment) were placed on a greenhouse bench under intermittent mist (as previously described) and arranged in a randomized complete block design. Weed seedling counts were recorded 2 and 4 weeks after sowing (WAS) and reported as percent germination. The shoot fresh weight (SFW) was recorded 8 WAS then converted to a percent reduction in shoot fresh weight compared to the non-treated control (% Reduction in SFW $= \frac{\textbf{Non-treated (average SFW)} - \textbf{Treatment (SFW)}}{\textbf{Non-treated (average SFW)}} \times 100$).

Rooting percentage data were analyzed with generalized linear models using the binary distribution and a logit link function using the GLIMMIX procedure of SAS (Version 9.4; SAS Institute Inc., Cary, NC, USA). All other data were analyzed with linear models using the GLIMMIX procedure of SAS, and differences between treatment means were determined using the Shaffer-Simulated method ($p < 0.05$).

3. Results

3.1. Propagation Trial

The butterfly bush rooting percentage was 80% or greater for all treatments except for pine pellets (72%), isoxaben + dithiopyr (36%), and isoxaben (20%) (Table 2). The root dry weight was 70% lower for isoxaben but was similar for all other treatments compared to the non-treated control. Although isoxaben + dithiopyr had a low rooting percentage, the root dry weight for the rooted cuttings was similar to the non-treated control. The shoot dry weight was also lowest for isoxaben, reduced by 74% compared to the non-treated control. Although shoot dry weight was numerically greater for oxyfluorfen + oxadiazon and indaziflam, all treatments (except isoxaben) had a shoot dry weight similar to the non-treated control. Sufficient rooting was not achieved for isoxaben and isoxaben + dithiopyr; thus, they were not included in the transplant study.

Table 2. Rooting response of butterfly bush and crape myrtle cuttings treated with four preemergence herbicides and two mulches.

	Rooting Percentage (%)	Root dry Weight (g)	Shoot dry Weight (g)	Total Root Length (cm)	Root Surface Area (cm^2)	Root Volume (cm^3)	Root Average Diameter (mm)
Treatment [z]				**Butterfly bush (*Buddleja davidii* 'Nanho Blue')**			
Non-treated control	84 a [y]	0.20 ab	0.58 ab	n/a	n/a	n/a	n/a
isoxaben	20 c	0.06 b	0.15 b	n/a	n/a	n/a	n/a
oxyfluorfen + oxadiazon	80 a	0.24 a	0.90 a	n/a	n/a	n/a	n/a
isoxaben + dithiopyr	36 bc	0.17 ab	0.57 ab	n/a	n/a	n/a	n/a
indaziflam	88 a	0.26 a	0.69 ab	n/a	n/a	n/a	n/a
Rice hull mulch	84 a	0.21 ab	0.46 b	n/a	n/a	n/a	n/a
Pine pellet mulch	72 ab	0.19 ab	0.36 b	n/a	n/a	n/a	n/a
				Crape myrtle (*Lagerstroemia indica* 'Catawba')			
Non-treated control	88 a	0.07 a	n/a	222 ab	39 ab	0.565 a	0.610 ab
isoxaben	92 a	0.06 a	n/a	130 b	26 b	0.439 a	0.697 a
oxyfluorfen + oxadiazon	96 a	0.11 a	n/a	326 a	59 a	0.873 a	0.584 b
isoxaben + dithiopyr	80 a	0.10 a	n/a	298 ab	54 ab	0.789 a	0.594 ab
indaziflam	92 a	0.09 a	n/a	273 ab	49 ab	0.703 a	0.590 b
Rice hull mulch	84 a	0.08 a	n/a	230 ab	41 ab	0.591 a	0.585 b
Pine pellet mulch	88 a	0.09 a	n/a	270 ab	47 ab	0.656 a	0.574 b

[z] Preemergence herbicides (low labeled rate) and mulches [1.3 cm (0.5 inch) depth] were applied prior to sticking cuttings in 6.4 cm (2.5 inch) diameter square containers. [y] Means followed by different letters within columns indicate significant difference at $p < 0.05$ using the Shaffer-Simulated method for multiple comparisons.

For crape myrtle, the rooting percentage ranged from 80 to 96% and there were no differences among the treatments (Table 2). Root dry weight was similar for all treatments, but numerically was 29 to 57% greater for oxyfluorfen + oxadiazon, isoxaben + dithiopyr, indaziflam, and pine pellets compared to the non-treated control. Root length and root surface area were numerically lowest for isoxaben and greatest for oxyfluorfen + oxadiazon, but all treatments were similar to the non-treated control. Root volume was similar among all treatments, but all root volumes were numerically greater (5 to 55%) compared to the non-treated control except for isoxaben. There were no differences in average root diameter compared to the non-treated control.

3.2. Transplant Trial

After rooted cuttings were transplanted, butterfly bush shoot height was similar to the non-treated control at 1 and 2 MAT (Table 3). Shoot width was greatest for indaziflam at 1 MAT, but similar to the non-treated control for all other treatments at 1 and 2 MAT. Leaf greenness was not affected by any of the treatments and was similar to the non-treated control at 1 and 2 MAT. Substrate pH was not affected by any of the treatments throughout the transplant study and was similar to non-treated control. Substrate electrical conductivity (EC) was greatest for oxyfluorfen + oxadiazon and rice hulls at 1 MAT, whereas all other treatments had EC similar to the non-treated control for both months. At 2 MAT, butterfly bush root and shoot dry weight and flower number were similar to the non-treated control for all the treatments (Table 3).

Table 3. Growth response (after transplant to 2.4 L containers) of butterfly bush and crape myrtle rooted cuttings treated with four preemergence herbicides and two mulches.

	Shoot Height (cm)			Shoot Width (cm)			Root Dry Weight (g)	Shoot Dry Weight (g)
	Months after Treatment							
	1	2	3	1	2	3		
Treatment [z]	**Butterfly bush (*Buddleja davidii* 'Nanho Blue')**							
Non-treated control	14.1 a [y]	48.4 a	n/a	23.7 b	55.4 a	n/a	2.26 a	25.09 a
isoxaben	-	-	n/a	-	-	n/a	-	-
oxyfluorfen + oxadiazon	12.8 a	48.1 a	n/a	21.9 b	55.5 a	n/a	1.98 a	21.22 a
isoxaben + dithiopyr	-	-	n/a	-	-	n/a	-	-
indaziflam	19.2 a	52.0 a	n/a	33.3 a	55.1 a	n/a	2.49 a	26.38 a
rice hulls	17.6 a	47.3 a	n/a	27.1 ab	59.3 a	n/a	2.32 a	24.24 a
pine pellets	14.3 a	49.4 a	n/a	23.2 b	53.3 a	n/a	1.94 a	21.11 a
	Crape myrtle (*Lagerstroemia indica* 'Catawba')							
Non-treated control	25.9 a	30.8 a	32.1 a	17.6 a	24.8 a	26.0 a	1.36 a	6.02 a
isoxaben	24.5 a	27.9 a	27.8 a	14.3 a	19.1 a	19.8 a	1.29 a	4.71 a
oxyfluorfen + oxadiazon	27.1 a	34.4 a	36.0 a	16.4 a	28.4 a	29.3 a	1.89 a	7.86 a
isoxaben + dithiopyr	28.7 a	33.6 a	34.3 a	16.8 a	23.0 a	23.9 a	1.69 a	6.12 a
indaziflam	20.3 a	25.3 a	26.0 a	13.4 a	19.4 a	21.6 a	1.16 a	5.03 a
Rice hull mulch	22.4 a	27.0 a	27.4 a	13.3 a	20.5 a	20.7 a	1.22 a	4.97 a
Pine pellet mulch	25.4 a	28.4 a	28.4 a	16.4 a	21.8 a	23.3 a	1.44 a	7.31 a

[z] Preemergence herbicides (low labeled rate) and mulches [1.3 cm (0.5 inch) depth] were applied prior to sticking cuttings in 6.4 cm (2.5 inch) diameter square containers. [y] Means followed by different letters within columns indicate significant difference at $p < 0.05$ using the Shaffer-Simulated method for multiple comparisons.

After transplant, crape myrtle height and width were similar among all the treatments at 1, 2, and 3 MAT (Table 3). Leaf greenness at 1, 2 and 3 MAT was similar to the non-treated control for all the treatments. Substrate pH and EC were similar to the non-treated control for all the treatments throughout the transplant study. Shoot and root dry weight was similar to non-treated control for all the treatments at the end of the study.

3.3. Weed Efficacy Trial

Weed seed germination for the non-treated controls was over 75% at 4 WAS for all weed species (Table 4). Creeping woodsorrel germination was <10% for all preemergence herbicides and mulches except for indaziflam (23%) and rice hulls (11%) at 2 WAS and for indaziflam (34%) and pine pellets (14%) at 4 WAS. All treatments reduced the shoot fresh weight of creeping woodsorrel by >88% except for indaziflam (58%) (Table 5). Bittercress germination was 32 to 86% lower than the non-treated control for all treatments at 2 WAS and 43 to 100% lower for all treatments at 4 WAS. At 4 WAS, germination was <10% for isoxaben, oxyfluorfen + oxadiazon, and rice hull mulch. Shoot fresh weight for bittercress was reduced by over 77% except for indaziflam (35%). Germination for crabgrass was lower for all treatments except for indaziflam compared to the non-treated control at 4 WAS. Crabgrass shoot fresh weight was reduced by over 91% for isoxaben, oxyfluorfen + oxadiazon, isoxaben + dithiopyr, and pine pellet mulch. Mulberry weed germination was reduced 48 to 77% for all preemergence herbicides and mulches compared to the non-treated control at 4 WAS. Shoot fresh weight was 91 to 98% lower for all treatments except indaziflam (82%).

Table 4. Percent germination (2 and 4 weeks after sowing—WAS) of seeds for four weed species (creeping woodsorrel, hairy bittercress, large crabgrass, and mulberry weed) sown to containers treated with four preemergence herbicides and two mulches.

	Creeping Woodsorrel (*Oxalis corniculata*)		**Hairy Bittercress (*Cardamine hirsuta*)**		**Large Crabgrass (*Digitaria sanguinalis*)**		**Mulberry Weed (*Fatoua villosa*)**	
	WAS		**WAS**		**WAS**		**WAS**	
	2	**4**	**2**	**4**	**2**	**4**	**2**	**4**
Treatment [z]	**Germination (%)**							
Non-treated control	28.8 a [y]	89.4 a	87.0 a	76 a	92.0 a	84.0 a	56.9 a	80.0 a
isoxaben	1.3 c	0.0 d	20.5 de	0.0 d	59.5 bc	51.5 bc	8.1 c	2.5 c
oxyfluorfen + oxadiazon	7.5 c	8.1 cd	54.5 b	9.5 cd	31.5 d	18.5 d	11.9 c	2.5 c
isoxaben + dithiopyr	8.1 c	9.4 cd	47.0 bc	30.5 b	75.5 ab	22.5 d	22.5 bc	23.8 b
indaziflam	22.5 ab	33.8 b	46.0 bc	33.0 b	71.5 abc	67.0 ab	31.9 b	31.9 b
Rice hull mulch	10.6 bc	9.4 cd	31.5 cd	9.5 cd	56.0 bc	33.5 cd	31.9 b	10.0 c
Pine pellet mulch	3.8 c	14.4 c	0.5 e	17.5 c	51.0 cd	45.5 c	5.6 c	22.5 b

[z] Preemergence herbicides (low labeled rate) and mulches [1.3 cm (0.5 inch) depth] were applied prior to sticking cuttings in 6.4 cm (2.5 inch) diameter square containers. [y] Means followed by different letters within columns indicate significant difference at $p < 0.05$ using the Shaffer-Simulated method for multiple comparisons.

Table 5. Percent reduction in shoot fresh weight (compared to the non-treated control; eight weeks after sowing) of four weed species (creeping wood sorrel, hairy bittercress, large crabgrass, and mulberry weed) from seeds sown to containers treated with four preemergence herbicides and two mulches.

	Creeping Wood Sorrel (*Oxalis corniculata*)	**Hairy Bittercress (*Cardamine hirsuta*)**	**Large Crabgrass (*Digitaria sanguinalis*)**	**Mulberry Weed (*Fatoua villosa*)**
Treatment [z]	**Reduction in shoot fresh weight (%)**			
Non-treated control	-	-	-	-
isoxaben	100.0 a [y]	99.4 a	92.4 a	98.3 a
oxyfluorfen + oxadiazon	99.8 a	98.6 a	95.4 a	97.6 a
isoxaben + dithiopyr	99.1 a	97.8 a	100.0 a	96.1 a
indaziflam	57.9 c	35.2 b	53.7 b	82.1 b
Rice hull mulch	88.7 b	78.0 a	54.6 b	91.9 a
Pine pellet mulch	95.9 a	87.0 a	91.8 a	91.6 a

[z] Preemergence herbicides (low labeled rate) and mulches [1.3 cm (0.5-inch) depth] were applied prior to sticking cuttings in 6.4 cm (2.5-inch) diameter square containers. [y] Means followed by different letters within columns indicate significant difference at $p < 0.05$ using the Shaffer-Simulated method for multiple comparisons.

4. Discussion

The preemergence herbicides used in our study during cutting propagation of butterfly bush and crape myrtle did not negatively affect the crops after transplant. The butterfly bush cutting rooting percentages, along with root and shoot growth, were negatively affected by isoxaben, while isoxaben + dithiopyr significantly reduced the rooting success of butterfly bush. Isoxaben and isoxaben + dithiopyr are not labeled for use on butterfly bush and certain crop species may be sensitive to these active ingredients. Polomski et al. [18] reported that rooted cuttings of butterfly bush were injured when treated with a sprayable formulation of isoxaben (Gallery DF), but no damage was observed from a granular formulation of isoxaben + oryzalin (Snapshot 2.5 TG). Witcher and Poudel [13] reported severe damage (only 5% rooting) to butterfly bush cuttings treated 2 weeks after sticking with a sprayable formulation of isoxaben (Gallery SC). In a study by Davies and Duray [7], dithiopyr (Dimension) was applied after sticking cuttings and suppressed root development during propagation and subsequent liner growth for 'White Lephrechaun' hibiscus (*Hibiscus rosa-sinensis* L.). Dithiopyr belongs to the pyridine herbicide family but has a mode of action similar to dinitroaniline herbicides including inhibition of cell division and reduce root elongation, which could have contributed to the negative effects isoxaben + dithiopyr had on butterfly bush in our study. Penney et al. [19] noted isoxaben + dithiopyr is safe to apply on many sensitive ornamental crop species in nursery production, but the present study is the first reported use of isoxaben + dithiopyr during cutting propagation. Future research to screen additional crop species listed on the isoxaben + dithiopyr product label may expand potential use in cutting propagation.

Although isoxaben should be avoided in butterfly bush, it had no effect on crape myrtle rooting and subsequent growth in our study. Other studies have shown that isoxaben can be safely used in cutting propagation of several ornamental crop species, including 'Dwarf Burford' holly, 'Ruby' loropetalum, and "Mariesii' viburnum [10,13]. Isoxaben is labeled for use on many crop species during production and has been shown to be safe when applied after transplant [19–21]. For indaziflam, no detrimental effects were observed on root or shoot growth of butterfly bush or crape myrtle during propagation, corresponding to previous reports with indaziflam on propagation of butterfly bush (*Buddleja davidii* 'Nanho Blue'), holly (*Ilex cornuta* 'Dwarf Burford'), rose (*Rosa* 'Radrazz') and viburnum (*Viburnum odoratissimum* Ker Gawl. and *Viburnum plicatum f. tomentosum* Thunb. 'Mariesii') [13,14]. In our transplant trial, no residual effect on subsequent growth of butterfly bush or crape myrtle plants was observed for indaziflam. Nevertheless, growers should take caution when using preemergence herbicides during the propagation and testing of individual crop species to ensure safety on rooting and post-transplant growth.

Weed control efficacy varied by herbicide and weed species. Isoxaben, isoxaben + dithiopyr, and oxyfluorfen + oxadiazon provide over 92% control for all four weed species while indaziflam only provided 57% (creeping woodsorrel), 35% (bittercress), 53% (crabgrass), and 82% (mulberry weed) control. In a previous study, indaziflam provided slightly better control (75%) of crabgrass but tended to not perform as well as isoxaben or oxyfluorfen + oxadiazon on creeping wood sorrel, bittercress, crabgrass, or mulberry weed. In other studies, indaziflam has not provided effective control of bittercress under typical nursery production conditions (personal communication). Although indaziflam is tightly bound to soil and pine bark particles which prevent leaching, it is possible that the high moisture content of the propagation environment led to increased degradation resulting in reduced weed control. In the current study, weed seeds were sown on the substrate surface to simulate weed seed dispersal via wind or force dehiscence which is commonly encountered in a nursery setting [22]. Container substrates used for nursery crop propagation are typically weed seed-free; thus, it is clear that most weeds are introduced from the surrounding areas.

Pine pellets and rice hulls did not affect root or shoot growth in either trial, similar to previous reports of these mulches used in propagation of butterfly bush, crape myrtle, holly, hydrangea (*Hydrangea paniculata* Siebold 'Phantom'), and viburnum [13,15]. Both mulches provided over 91% control of mulberry weed and over 78% control of bittercress, yet pine pellets provided better control of creeping wood sorrel and crabgrass compared to rice hulls. Poudel and Witcher [15] also reported variable weed control of rice hulls in propagation. Pine pellets form a solid surface after saturation with water. Weed seeds germinate on the surface, but roots cannot penetrate the mulch layer to access nutrients in the substrate and subsequently remain alive but do not grow. Mulches provide a non-chemical alternative to preemergence herbicides in nursery propagation, especially useful for herbicide sensitive crop species or for growers concerned about herbicide runoff in irrigation collection ponds. Although off-target applications can leach into the soil or be distributed into surface water, most preemergence herbicides bind to the container substrate particles which prevents leaching from the container [23].

5. Conclusions

Although the adoption of sanitation practices can help prevent the growth of weeds during propagation, once weeds become established, propagators have few options for effective control. Hand weeding is labor-intensive and expensive; thus, more efficient weed control methods need to be identified to reduce weed competition during propagation and to prevent spreading weeds into the production stage. Although there are no preemergence herbicides labeled for use in propagation, we have demonstrated several products that are safe to use during propagation and had no lingering negative effects on plant growth after transplant. In particular, the combination of oxyfluorfen + oxadiazon has demonstrated a high level of crop safety and weed efficacy on numerous weed species. In enclosed structures where preemergence herbicides cannot be used, mulches are a viable option for preventing weed establishment without hindering crop growth. Prior to adopting these alternative weed control practices, growers should test them on small groups of individual crop species to verify crop safety prior to large-scale implementation.

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