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Herbicide Formulation Affects Weed Control and Crop Tolerance in Greenhouse Ornamentals

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Abstract. **Weed control in container-grown ornamentals can be improved by careful herbicide selection. Four studies were conducted in greenhouses at Oregon State University to improve the understanding of how differences in the mode of action and formulation of herbicides can affect bryophyte control efficacy and crop safety. Granular (G) formulations of pendimethalin and indaziflam were compared with sprayable liquid (L) formulations of pendimethalin, indaziflam, and dimethenamid-p as well as with a nontreated control on four perennial container-grown ornamentals. Indaziflam in the L formulation performed better than that in the G formulations for controlling hairy bittercress up to 20 weeks after the initial treatment. Dimethenamid-p was more effective than indaziflam for liverwort and moss control. Pendimethalin in the G formulation less effectively controlled hairy bittercress than the L formulation did, but it performed better against moss during a second study. The L formulation of indaziflam injured Japanese pachysandra and boxwood and reduced root and shoot growth by 10% to 29%. Dimethenamid-p provided excellent control of the weed species tested and was safe for the crops, indicating its potential use as an alternative to hand-weeding in greenhouses.**

The US ornamental horticulture industry has a significant share of specialty crop values and a farm gate crop value of approximately $13.8 billion in 2019 (US Department of Agriculture, National Agricultural Statistics Service 2020). The ornamental sector includes wholesale nurseries, commercial greenhouses, turfgrass, and associated industries and distribution channels. In 2018, this sector employed more than 1.3 million people (Hall et al. 2020). Commercial greenhouse production is high-intensity and high-input agriculture that is performed to ensure the production of high-quality, uniform, and consistent crops that rely on irrigation, fertilization, and pest control. Certain nursery crops are typically propagated from cuttings, also known as liners, in a greenhouse. This greenhouse environment is also conducive to weed growth. Several weeds spread rapidly in nurseries and greenhouses across the United States, including higher plants such as broadleaves (Dicotyledoneae) and grasses (Poaceae) as well as primitive plants like algae (Chlorophyta, Charophyta), liverworts (Marchantiophyta), and mosses (Bryophyta) (Fausey 2003). Liverworts and mosses thrive in environments with high humidity and fertility. Bryophyte weeds can become a problem for plant nurseries because they can impede water movement to the root zone, direct nutrients away from the crop, and reduce the market value of the crop (Sidhu et al. 2020). Options that minimize bryophyte weed pressure include the application of mulches (Altland and Krause 2014), changing irrigation and fertilization practices (Saha et al. 2019; Sidhu et al. 2020), and altered lighting conditions (Mache and Loiseaux 1973). Infestations may still occur despite these and other preventative measures.

An underexplored option for plant propagation is chemical weed control. Products labeled for postemergence control in greenhouses include acetic acid, ammonium nonanoate, d-limonene, pelargonic acid, and sodium carbonate peroxyhydrate (Marble et al. 2017; Sidhu et al. 2020). Most of these options must be spot-applied and only provide short-term control of bryophyte weeds. They require repeated applications and higher labor costs for effective control, and young plants may be damaged by the treatments.

Although more practical and effective options exist for the chemical control of bryophytes, none is labeled for greenhouse use. Regarding container-grown plants, preemergence herbicides dithiopyr, oryzalin, flumioxazin, oxyfluorfen, and oxadiazon have shown promise as options for liverwort control applied as a granular (G) formulation (Fausey 2003; Senesac and Tsontakis-Bradley 1997). Product formulation may affect efficacy and crop tolerance. In these studies, G pendimethalin (WSSA group 3: inhibitors of microtubule assembly) treatments were ineffective in Alabama but provided moderate liverwort control in Oregon (Newby et al. 2007).

The product formulation may affect efficacy and crop tolerance. The G formulations of flumioxazin may not control liverwort as effectively as the water-dispersible G formulation (Sidhu et al. 2020), but this difference was not observed during some experiments (Fausey 2003). Although G oxyfluorfen is less effective than an emulsifiable concentrate formulation for liverwort control, it is not less effective for silver thread-moss (Fausey 2003). The G formulations of pendimethalin and dimethenamid-p (group 15) combined with pendimethalin provide poor liverwort control (Hester et al. 2012; Newby et al. 2007). However, an emulsifiable concentrate of dimethenamid-p was effective for pre-emergence and postemergence liverwort control (Hester et al. 2012; Marble et al. 2017). A soluble concentrate (SC) formulation of indaziflam was also moderately effective at controlling liverwort, but the G formulations were not tested (Hester et al. 2012).

Gaps exist in our knowledge of the interaction between product formulation and the active ingredients affecting liverwort control in container-grown ornamentals. Group 3 herbicides (pendimethalin and oryzalin) have shown promise as options for the control of liverwort (Newby et al. 2007; Senesac and Tsontakis-Bradley 1997), but no comparison has been made between sprayable and G types. The G formulations of indaziflam are also available, but they have not been compared with the sprayable formulation, which has been shown to be moderately effective (Hester et al. 2012). None of the previous work has addressed differences in crop growth in response to herbicide treatments.

This study compared crop safety and weed control using liquid (L) and G formulations of indaziflam and pendimethalin herbicides and dimethenamid-p in an L formulation on four ornamental liners. A G formulation of dimethenamid-p was not available to include in our study. Our goal was to identify safe and effective treatments for bryophyte control in container-grown ornamentals by comparing the effect of the active ingredient and product formulation on bryophyte control and crop growth.

Materials and Methods

The greenhouse studies were conducted at the Oregon State University greenhouse facilities in Corvallis, OR, USA, between 2020 and 2021. The studies were initiated between

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October and November, and the greenhouses were maintained at 21 °C days, 18 °C nights, and a natural daylength. Plants were irrigated over the top daily as needed. Four different ornamental species were evaluated: *Gardenia jasminoides* and *Buxus* × 'Green Velvet' in 2020 and *Rosa* × 'Grace n Grit' and *Pachysandra terminalis* 'Green Sheen' in 2021 Plants were sourced in 50-cell flats from a local commercial nursery. Each plant was transplanted into a 3-L pot approximately 3 to 4 d before the initial treatments. A commercial sphagnum moss plus perlite potting mix was used (Sunshine Mix number 4; Sun Gro Horticulture, Agawam, MA, USA), and each pot was fertilized with 16–16–16 Endure fertilizer (J.R. Simplot Company, Boise, ID, USA) immediately following transplant placed on the pot surface. The experimental pots were organized in blocks and surrounded by trays containing common liverwort (*Marchantia polymorpha*), hairy bittercress (*Cardamine hirsuta*), and golden thread moss (*Leptobyrum pyriforme*) during the study duration to provide an infestation source.

Herbicides tested were pendimethalin at 4483 g a.i./ha in a G formulation (Pendulum 2G) or at 3330 g a.i./ha in an L formulation (Pendulum 3.3 emulsifiable concentrate). Indaziflam was tested at 50 g a.i./ha in a G formulation (Marengo G) and at 65 g a.i./ha in an L formulation (Marengo Flo). Dimethenamid-p (Tower) was tested in an L formulation at 1680 g a.i./ha. The tested rates mimic registered rates in different use patterns for ornamental crops. A nontreated control was included. A weed-free check was not included because the effects of weed competition were expected to be minimized because crop plants were transplanted into large weed-free containers with ample fertilizer and water. All treatments were applied within 7 d of transplanting and reapplied 60 d later. The L formulations were applied using a cabinet sprayer (Generation III Spray Chamber; De Vries Manufacturing, Hollendale, MN, USA). The chamber was equipped with an even flat-fan nozzle (8003XR; Teejet Spraying Systems, Glendale Heights, IL, USA) placed 50 cm above the canopy operating at 275 KPa and set to deliver 187 L·ha^{-1}. The G formulations were applied using a hand-held spreader (Scotts Wizz Spreader; The Scotts Company LLC., Marysville, OH, USA). All treatments were applied over the top of the crop, and the treated plants were moved back to the experimental location immediately after treatment. The studies were organized as a randomized complete block design with four replicates. A replicate consisted of three containers with a single crop plant per plot.

In the 2021 studies, liverwort inoculation was supplemented with a suspension of liverwort and water (1:1 w/w) made using a kitchen blender. One tablespoon of this suspension was poured on each pot within 1 week of initial herbicide applications. By 4 weeks after the initial treatment, no liverwort was seen in any of the experimental plots despite the inoculation and proximity of material capable of producing

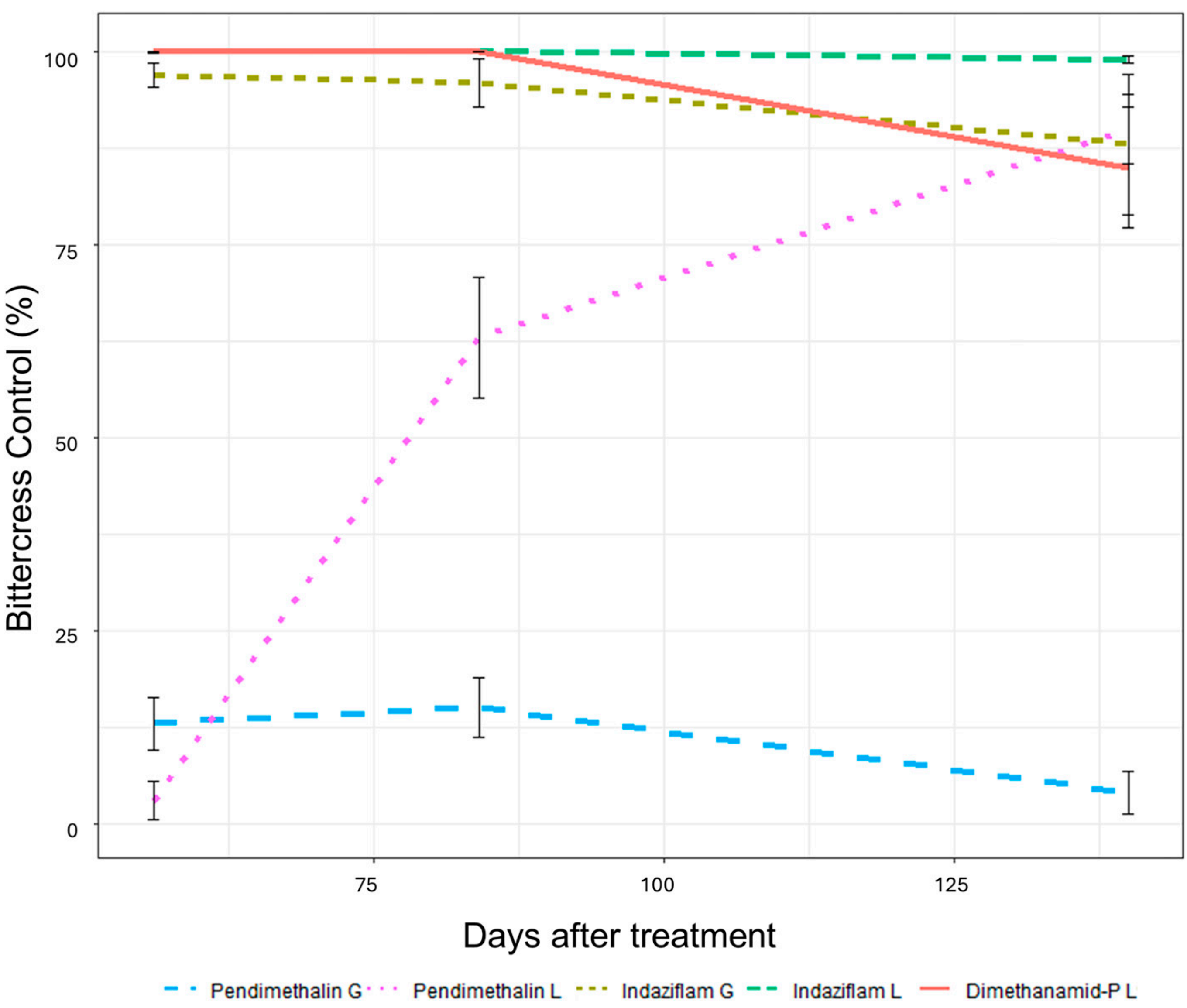

Fig. 1. Hairy bittercress (*Cardamine hirsuta*) was the primary weed in the 2020 studies. The data shown here are averaged between two studies (n = 8). Visual assessments were made until 20 weeks after treatment with five preemergence herbicides. Error bars represent the *SEM*. Treatments were applied at the start of the study and reapplied 60 d later.

spores; therefore, on 15 Nov 2021, liverwort fragments of approximately 5 cm^2 were transplanted into each pot.

Evaluations included visual assessments of weed control and phytochemical injury using a scale of 0% to 100% at 1, 2, 4, 8, 12, and 20 weeks after initial treatment (WAIT). At the end of the study, aboveground and belowground biomass were separately weighed. Height and width measured at two perpendicular directions were recorded for each plant to calculate the canopy volume using the formula for the volume of a cylinder. Weed and liverwort aboveground weight were collected, dried, and weighed for each pot.

Data analysis. A statistical analysis was performed using R 4.4.1 (R Core Team 2024). Canopy volume, crop weights, and weed dry biomass were analyzed with linear mixed models generated using R package LME4 (Bates et al. 2015). Weed control and phytochemical injury were analyzed using R package glmmTMB assuming a beta family distribution (Brooks et al. 2017). Treatments and species were considered fixed effects, whereas experimental blocks were treated as random effects. Effects were considered significant if an associated *P* value was less than 0.05. Dunnett's test was used for the post hoc analysis of phytochemical injury, canopy volume, and crop biomass using the DescTools R package (Signorell et al. 2024). The post hoc analysis of weed biomass and

Table 1. Golden thread-moss (*Leptobyrum pyriforme*) and hairy bittercress (*Cardamine hirsuta*) responses to herbicides 20 weeks after treatment during greenhouse studies in 2020. Efficacy data were combined for two studies (n = 8).

Treatment	Formulation[i]	Rate (g a.i./ha)	Moss[ii]	Bittercress	Bittercress wt (g)
			% Control		
Nontreated	—	—	—	—	38 b
Pendimethalin	G	4,483	100[iii] a	5 b	41.5 b
Pendimethalin	L	3,330	93 a	90 a	0.7 a
Indaziflam	G	50	86 ab	88 a	3.1 a
Indaziflam	L	65	52 b	99 a	0.0 a
Dimethenamid-p	L	1,681	97 a	85 a	0.5 a

[i] Treatments were applied at the start of the study and reapplied 60 d later.
[ii] Means followed by the same letter within columns are not statistically different according to Sidak's test.
[iii] Moss control associated with Pendimethalin G treatments was due to competition with uncontrolled bittercress weeds.
G = granular; L = liquid.

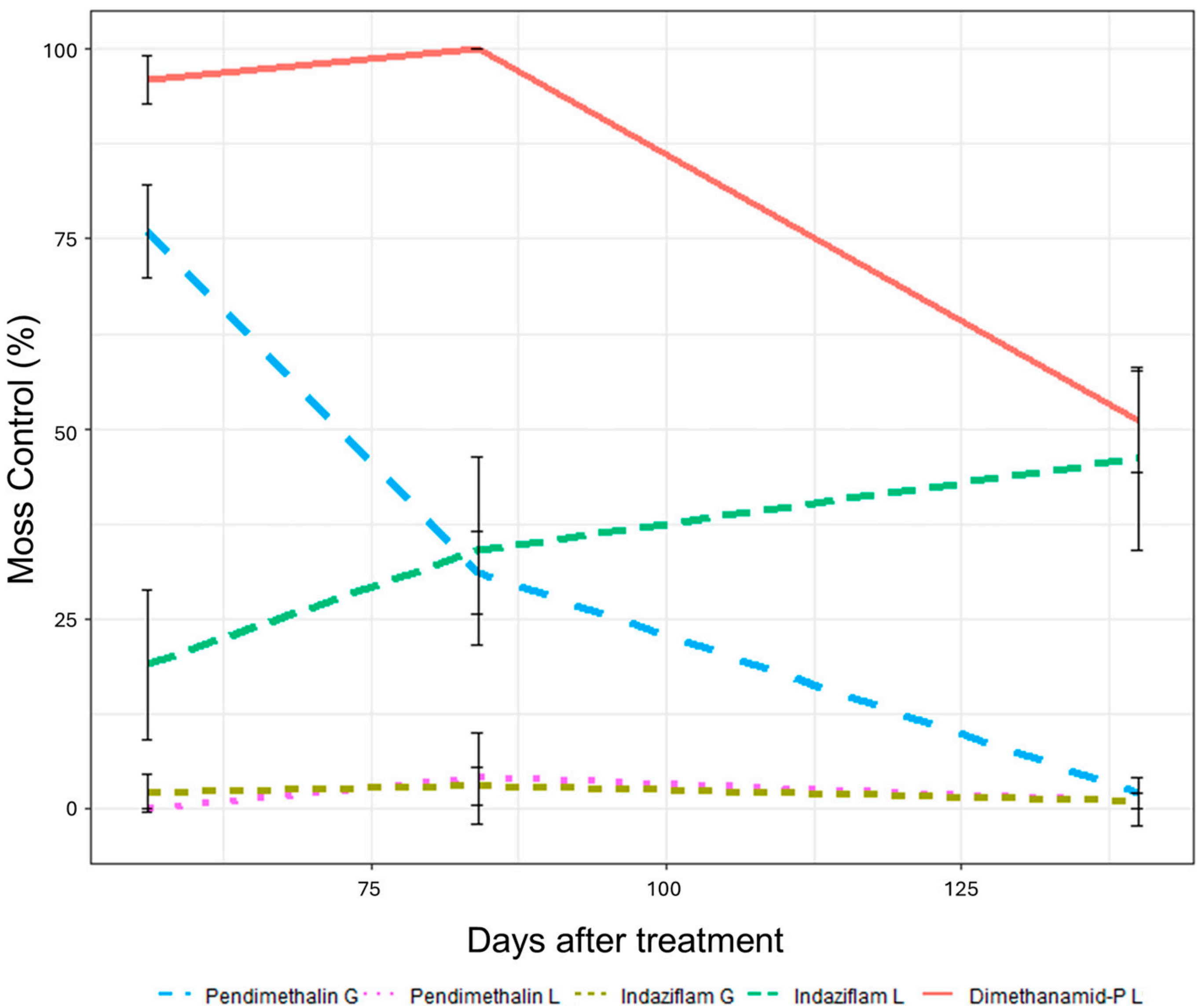

Fig. 2. Golden thread-moss (*Leptobyrum pyriforme*) was the primary weed in the 2021 studies. The data shown here are averaged between two studies (n = 8). Visual assessments were made until 20 weeks after treatment with five preemergence herbicides. Error bars represent the *SEM*. Treatments were applied at the start of the study and reapplied 60 d later.

Table 2. Liverwort (*Marchantia polymorpha*) and golden thread-moss (*Leptobyrum pyriforme*) responses to herbicides 20 weeks after treatment in greenhouse studies in 2021. Efficacy data were combined for two studies (n = 8).

Treatment	Formulation[i]	Rate (g a.i./ha)	Liverwort biomass[ii] Weight (g/pot)	Liverwort (%) Control	Moss control (%) Control	Weed biomass Weight (g/pot)
Nontreated	—	—	11 b	—	—	3.5 c
Pendimethalin	G	4,483	15 bc	19 a	3 a	1.4 ab
Pendimethalin	L	3,330	13 bc	30 a	4 a	3.0 bc
Indaziflam	G	50	20 c	6 a	1 a	2.3 bc
Indaziflam	L	65	9 ab	31 a	46 b	0.0 a
Dimethenamid-p	L	1,681	4 a	94 b	51 b	0.4 a

[i] Treatments were applied at the start of the study and reapplied 60 d later.
[ii] Means followed by the same letter within columns are not statistically different according to Sidak's test.
G = granular; L = liquid.

weed control was performed using the emmeans R package (Lenth 2019). A Šidák correction was used to control the family-wise error rate for multiple comparisons (Šidák 1967).

Results and Discussion

A combined analysis of weed control and biomass for each year was performed because no species-specific interactions were identified; however, weed control and biomass data for each year were analyzed separately because of the differences in weed species present.

Hairy bittercress (*Cardamine hirsuta*) was the dominant weed in the 2020 studies, with weed emergence observed by 8 WAIT. Indaziflam in G and L formulations and dimethenamid-p all controlled hairy bittercress at 80% or more during the study (Fig. 1, Table 1). At 20 WAIT, pendimethalin in the L formulation provided similar control levels, but indaziflam G continued to control nearly 100% of hairy bittercress (Fig. 1). Weed biomass harvested at 20 WAIT confirmed that pendimethalin L, indaziflam G and L, and dimethenamid-p provide reasonable control of hairy bittercress (Table 1). Some golden thread moss (*Leptobyrum pyriforme*) was observed in the 2020 studies, but pots with heavy bittercress competition made the moss distribution inconsistent across treatments. Moss coverage was highest in the indaziflam L treatment; however, this was also associated with the lowest hairy bittercress coverage (Table 1). Treatments that provided the highest hairy bittercress and moss control throughout the study were indaziflam G and dimethenamid-p.

Golden thread moss was the most common weed in the 2021 studies. The pendimethalin in the L formulation controlled moss through 8 WAIT, whereas dimethenamid-p controlled moss through 12 WAIT (Fig. 2). Dimethenamid-p and indaziflam L both continued to control moss at 20 WAIT, but at only 50% efficacy (Fig. 2, Table 2). Reductions in weed biomass, mostly hairy bittercress, were also seen with indaziflam L and dimethenamid-p treatments, but with reduced levels of control ranging from 46% to 51% (Table 2). Dimethenamid-p also controlled liverwort, and biomass measurements showed that growth was reduced by dimethenamid-p. Indaziflam L also reduced liverwort biomass, but visual assessments of control indicated that this herbicide had a lower rating than dimethenamid-p (Table 2). This was because the liverwort thallus was relatively green on the surface. Still, liverwort rhizoids were less substantial than those in the pendimethalin treatments.

Liverwort control in our study was only tested on transplanted pieces. It is possible that the environment was not conducive to liverwort growth because no spontaneous liverwort infestation was observed in any of the four studies. Marble et al. (2017) reported that dimethenamid-p provides variable levels of liverwort control and may be slow to act; therefore, the results reported here must be confirmed in an environment more favorable to liverwort growth.

Senesac and Tsontakis-Bradley (1997) identified group 3 herbicides oryzalin and dithiopyr, microtubule assembly inhibitors, and a group 14 herbicide, oxadiazon, which

Table 3. Pachysandra, Rosa, and Buxus phytochemical response, canopy volume, shoot weight, and root weight in response to preemergence herbicides 20 weeks after treatment during greenhouse studies in 2021.

Treatment	Formulation[i]	Rate (g a.i./ha)	Phytochemical injury (%)	Canopy volume (cm^3)	Canopy volume % change	Shoot wt (g/plant)	Shoot wt % change	Root wt (g/plant)	Root wt % change
Pachysandra terminalis									
Nontreated			0	1,842		8.8		6.5	
Pendimethalin	G	4,483	0	1,584	−14%	8.9	1%	5.5	−15%
Pendimethalin	L	3,330	0	1,694	−8%	9.8	11%	6.2	−5%
Indaziflam	G	50	0	1,809	−2%	9.2	5%	5.4	−17%
Indaziflam	L	65	45*	1,323	−28%	7.6	−14%	4.6	−29%
Dimethenamid-p	L	1,681	11	2,285	24%	9.5	8%	5.5	−15%
Rosa × 'Grace n Grit'									
Nontreated			0	10,449		8.7		8.0	
Pendimethalin	G	4,483	0	8,803	−16%	8.3	−5%	10.6	33%
Pendimethalin	L	3,330	0	12,937	24%	8.8	1%	8.4	5%
Indaziflam	G	50	0	10,155	−3%	7.5	−14%	7.8	−3%
Indaziflam	L	65	0	8,141	−22%	7.4	−15%	9.5	19%
Dimethenamid-p	L	1,681	0	9,274	−11%	7.8	−10%	10.0	25%
Buxus × 'Green Velvet'									
Nontreated			16	23,240		19.8		38.1	
Pendimethalin	G	4,483	8	28,066	21%	20.5	4%	37.9	−1%
Pendimethalin	L	3,330	5	18,654	−20%	18.7	−6%	47.5	25%
Indaziflam	G	50	0	31,179	34%	24.0	21%	47.1	24%
Indaziflam	L	65	23	17,358	−25%	16.6	−16%	34.2	−10%
Dimethenamid-p	L	1,681	13	18,181	−22%	20.4	3%	40.7	7%

[i] Treatments were applied at the start of the study and reapplied 60 d later.
[ii] Means followed by * within columns and species are not statistically different from nontreated according to Dunnet's test.
G = granular; L = liquid.

is a protoporphyrinogen oxidase inhibitor, as effective for suppressing liverwort. Fausey (2003) determined that group 14 herbicides flumioxazin and oxyfluorfen provided good liverwort control 11 WAIT after treatment at 74% and 58% control, respectively. Fausey's work also showed that postemergence treatments with flumioxazin and oxyfluorfen were among the most effective for controlling silver thread moss (85%–100% control) 2 WAIT. Newby et al. (2007) showed that flumioxazin controls liverwort at 40% to 88% 17 WAIT across three studies, and that oxyfluorfen plus oryzalin controlled liverwort at 28% to 87% 17 WAIT. None of the herbicides tested here was in group 14. In this study, pendimethalin, a group 3 herbicide, also suppressed liverwort (Fig. 2).

Phytochemical injury was induced by indaziflam L treatments on *B. microphylla* and *P. terminalis* (Table 3). Chlorosis and necrosis were noted, with whole leaves dying off in some cases. Compared with other treatments, indaziflam L also reduced the canopy volume in both species and reduced aboveground and belowground crop biomass in *B. microphylla* (Table 3). Indaziflam L treatments were also associated with the lowest canopy volume and root biomass of any treatment in *Rosa*, although the level was not statistically significant. *Rosa* sp. and *B. microphylla* are listed as safe on the indaziflam L label (Marengo SC). However, the product is not labeled for use in the greenhouse or application that exposes the crop foliage, as performed during this study. Palmer (2022) reported that the L formulation of indaziflam (SC) injured *B. microphylla* and *B. sempervirens* in some instances and concluded that more work is needed to determine whether *Buxus* species and hybrids are tolerant to indaziflam.

Pachysandra terminalis treated with dimethenamid-p exhibited some injury symptoms, but the biomass and canopy volume were unaffected, and the plants recovered completely (Table 3). Dimethenamid-p is labeled as safe for *Buxus* and *Rosa*, but it is not labeled for use in greenhouses. During our study, the *Buxus* canopy volume was reduced by dimethenamid-p treatments to degree similar to that associated with indaziflam SC. Palmer (2020) reported that dimethenamid-p applications injured *Buxus* sp. in a greenhouse study in 2010.

Crop safety data regarding *Gardenia* plants were removed from the analysis because of severe stress symptoms unrelated to herbicide treatments. This is likely because overwatering intended to promote liverwort growth. There was also some insect herbivory on *Buxus* plants that particularly affected the nontreated plots (Table 3).

Dimethenamid-p provides an effective option for the control of liverwort, hairy bittercress, and golden thread-moss control in potted ornamentals. *Pachysandra* plants injured by this treatment recovered well from their initial injury, and no severe stunting or injury was detected. This treatment showed some potential for use in greenhouse environments. The efficacy and safety of dimethenamid-p for liverwort control in greenhouses are aligned with previous findings (Hester et al. 2012; Marble et al. 2017; Sidhu et al. 2020). Both formulations of pendimethalin had inconsistent effects on bryophyte weeds. The L formulation reduced bittercress populations and moss growth in 2020, but not in 2021. Pendimethalin G exhibited moss control in 2021, but only through 8 WAIT.

The L formulation of indaziflam also exhibited control of all weeds tested, although with lower efficacy than dimethenamid-p. Injury observed on rose and pachysandra suggested that although this treatment is moderately effective, its use should be restricted to environments where crop safety has already been demonstrated. Indaziflam G provided lower control of golden thread-moss or liverwort transplants, demonstrating that the formulation of the indaziflam herbicides plays an important role in the efficacy of bryophyte control in container-grown plants. The lower rate of indaziflam G (50 g a.i.) could have contributed to the reduced efficacy, but because all treatments were reapplied within 60 d, the rate differences may be less relevant. Previous studies also reported adequate tolerance to indaziflam G in a greenhouse-grown *Buddleja davidii* (butterfly bush), *Illex cornuta* L. (Chinese holly), and *Lagerstroemia indica* L. (crepe myrtle) (Poudel and Witcher 2024; Witcher and Poudel 2020).

Weed control in the greenhouse is challenging; therefore, implementing sanitation practices is the first step. Preemergence herbicides may be used for weed control in propagation, but their use will be specific and affected by crop and herbicide formulation. In this study, dimethenamid-p was consistently effective for controlling problematic weeds and safe for the crops tested. Dimethenamid-p has the potential for use in greenhouse propagation. Future studies should explore dimethenamid-p effects on a broader range of crop species and identify how to implement this tool in commercial production to support its registration in greenhouses.

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