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Influence of carrier water pH and hardness on imazapic efficacy for sicklepod (*Senna obtusifolia* L.) control in peanut

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Research Article

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Abstract

Carrier water quality is an important consideration for herbicide efficacy. Field and greenhouse studies were conducted from 2021 to 2023 to evaluate the effect of carrier water pH and hardness on imazapic efficacy for sicklepod control in peanut crops. In separate field experiments imazapic was applied postemergence at 0.071 kg ai ha^{-1} with carrier water pH levels of 5, 6, 7, 8, or 9; and hardness levels of 0 (deionized water), 100, 200, 400, or 500 mg L^{-1} of $CaCO_3$ equivalent. In greenhouse experiments, imazapic was applied to sicklepod that was either 10 cm, 15 cm, or 20 cm tall at similar carrier water pH levels and hardness levels of 0, 100, 200, 400, or 800 mg L^{-1} of $CaCO_3$. In the field study, sicklepod control, density, and biomass reductions were lower with carrier water pH 5 or 9 compared with pH 7. In the greenhouse study, control was not different among carrier water pH levels when imazapic was applied to 10-cm-tall sicklepod; however, when applied to 15- or 20-cm-tall sicklepod, control was at least 25% greater with acidic (pH 5) compared to alkaline (pH 9) carrier water. Results from the field study showed that carrier water hardness ≤500 ppm did not reduce the efficacy of imazapic to control sicklepod. In the greenhouse study, regardless of sicklepod height, carrier water hardness of 800 mg L^{-1} reduced sicklepod control by 15% and biomass reduction by 17% compared with deionized water (pH 7). The effects of carrier water pH and hardness on imazapic efficacy did not compromise peanut yield in the field study. However, this study indicates that both acidic and alkaline carrier water pH and hardness (800 mg L^{-1} $CaCO_3$ L^{-1}) have the potential to reduce imazapic efficacy on sicklepod, and appropriate spray solution amendments maybe be needed to maintain optimum efficacy.

Introduction

Sicklepod is one of the most predominant annual broadleaf weeds in peanut production in the southeastern United States (Daramola et al. 2023a; Sosnoskie et al. 2021). Native to tropical and subtropical parts of South and North America, sicklepod has spread and become an important weed across much of the southeastern United States (Norsworthy 2003; Webster and Nichols 2012). A survey of more than 1,700 growers in Georgia reported sicklepod as the fifth most challenging of all agricultural pests, including weeds, insects, and diseases (Culpepper et al. 2020). Sicklepod has also become a troublesome weed in other southeastern U.S. agronomic crops such as cotton (*Gossypium hirsutum* L.), peanut, and soybean [*Glycine max* (L.) Merr.] (Daramola et al. 2023b; Sosnoskie et al. 2021; Webster and MacDonald 2001). Sicklepod is difficult to control due to its extended emergence period (May to September); high seed production (up to 45 million seeds ha^{-1}); hard seed coat, which enhances its persistence in the soil seedbank; and large seed size, which enables germination from deeper soil depths (Bridges and Walker 1987; Egley and Chandler 1978; Taylor and Oliver 1997). Sicklepod can be very difficult to control in peanut crops partly because they are both members of the same plant family, Fabaceae. Thus, sicklepod tolerates many of the herbicides used for weed control in peanut crops (De Moraes et al. 2020). Sicklepod can grow above the peanut canopy around midseason and can interfere with fungicide deposition and intercept photosynthetic active radiation at the expense of the crop, causing significant yield reduction (Hauser et al. 1975; Wilcut et al. 1994). Hauser et al. (1982) reported that one sicklepod plant in a 10-m^{-2} area reduced peanut yield by 6.1 to 22.3 kg ha^{-1}.

Imazapic is one of the most commonly used postemergence (POST) herbicides for sicklepod control in peanut crops in the southeastern United States (Daramola et al. 2023a, 2023b; Grey et al. 2003). Since its introduction in 1996, imazapic has been widely used because it provides effective control of the most troublesome weeds in peanut without the need to mix it with other herbicides (Grey et al. 2003). About 31% of the U.S. peanut crop is treated with imazapic making it the second most used POST herbicide after 2,4-DB (USDA-NASS 2019). Imazapic is an imidazolinone herbicide that kills susceptible weeds by inhibiting acetolactate synthase (Senseman 2007). Imazapic at the recommended use rate of 71 g ai ha^{-1} provides effective (85% to 95%) control of sicklepod (Grey et al. 2003; Wehtje and Brecke 2004; Wehtje et al. 2000). However, in recent years, some growers have anecdotally observed reduced efficacy of imazapic on sicklepod. Variability in environmental factors across years and locations and growth stage/weed size was hypothesized as potential causes for the inconsistent sicklepod control (De Moraes et al. 2020). Weed growth stage can have a profound effect on the performance of POST herbicides, which can vary between herbicides and weed species (Kudsk 2008). Wehtje et al. (2000) reported that efficacy of imazapic was greater on Florida beggarweed (*Desmodium tortuosum* L.) at the unifoliate leaf stage than the trifoliate leaf stage. Similarly, imazapic provided only marginal control of Palmer amaranth (*Amaranthus palmeri* L.) and *Ipomoea* spp. that are large in size (Chahal et al. 2011; Lancaster 2007). One factor, however, that is often neglected for poor herbicide performance is carrier water quality such as pH and hardness (Daramola et al. 2022).

The pH and hardness of water used in an herbicide mixture can vary depending on geographic location and water source (Freeze and Cherry 1979). In the United States, water pH ranges from 3 to 9 (Deer and Beard 2001). A recent survey conducted in the Florida panhandle also showed a significant variation in water pH (4.57 to 8.20) and hardness (17 to 222 $CaCO_3$ ppm) (Carter and Devkota 2019). This variability in water quality used in a herbicide mixture can contribute to inconsistent herbicide efficacy (Devkota and Johnson 2016). Carrier water pH can influence the efficacy of weak-acid herbicides by affecting the solubility, hydrolysis, dissociation, or chemical breakdown of the herbicide molecules (Roskamp et al. 2013). Devkota et al. (2016) reported that the efficacy of mesotrione on horseweed (*Conyza canadensis* L.) was greater when it was applied with carrier water pH 6.5 compared with pH 4 or 9. In other studies, the efficacy of glufosinate on Palmer amaranth and horseweed, and glyphosate on common ragweed (*Ambrosia artemisiifolia*), horseweed, and Palmer amaranth was greater when applied at carrier water pH 4 compared with pH 9 (Devkota and Johnson 2016, 2019, 2020). Likewise, various studies have reported hard-water antagonism of divalent and polyvalent cations on weak-acid herbicides due to the formation of a herbicide-salt complex, which is not readily absorbed or translocated by targeted plants (Devkota et al. 2016; Nalewaja et al. 1991; Roskamp et al. 2013). The efficacy of glufosinate and mesotrione on giant ragweed (*Ambrosia trifida* L.), horseweed, and Palmer amaranth was reduced by at least 17% with increasing carrier water hardness from 0 to 1,000 mg L^{-1}. Imazapic, with an acid dissociation constant (pKa) of 3.6 and solubility of 2,200 mg L^{-1} at 25 C is a weak-acid herbicide and may be susceptible to hard-water antagonism and affected by carrier water pH. Information on the effect of carrier water pH and hardness is important in developing recommendations for improved herbicide efficacy on problematic weed species. Currently, no published information exists on the effect of carrier water quality on the efficacy of imazapic on peanut crops. Therefore, field and greenhouse studies were conducted to evaluate the effect of carrier water pH and hardness on the efficacy of imazapic for sicklepod control in peanut, in an attempt to understand whether this could be part of the reduced efficacy observed by growers.

Materials and Methods

Field Experiments

Two field experiments were conducted at the West Florida Research and Education Center in Jay, FL (30.776542°N, 87.147662°W)) during the summer of 2021, and both experiments were repeated in 2022. The experiments were established on sandy loam soil with 1.6% organic matter and natural sicklepod infestation. Peanut cultivar 'Georgia-06G' (Branch 2007) was planted at 20 seeds m^{-1} in rows that were 91 cm wide. Plots size was 7.6 × 3.6 m in both years. Planting occurred on June 5, 2021, and June 3, 2022. The two experiments (carrier water pH and carrier water hardness) were randomized complete block designs with four replications in both years. Pendimethalin [N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine] (Prowl® H2O; BASF Corporation, Research Triangle Park, NC) was applied via broadcast across the entire plot area at 1.1 kg ai ha^{-1} immediately after planting peanut to provide preemergence weed control in both years. In addition, clethodim [(2-[(E)-N-[(E)-3-chloroprop-2-enoxy]-C-ethylcarbonimidoyl]-5-(2-ethylsulfanylpropyl)-3-hydroxycyclohex-2-en-1-one] (Select Max; Valent USA Corporation, Walnut Creek, CA) was sprayed at 136 g ai ha^{-1} at 42 d after planting (DAP) to provide grass weed control. A CO_2-pressurized backpack sprayer with TeeJet TTI11002 nozzles (Spraying Systems Co., Glendale Heights, IL) calibrated to deliver 140 L ha^{-1} spray volume at 4.8 km h^{-1} was used to spray treatments in both years. A nontreated check was included for treatment evaluation in both experiments. Sicklepod plants were 5 cm to 30 cm tall and density was 70 to 150 plants m^{-2} at time of treatment.

To test the effect of carrier water pH, imazapic [5-methyl-2-[4-methyl-5-oxo-4-(propan-2-yl)-4,5-dihydro-1H-imidazol-2-yl] pyridine-3-carboxylic acid] (Cadre; BASF Corporation) was applied 35 DAP at 0.071 g ai ha^{-1} with a nonionic surfactant (NIS 0.25% v/v, Preference; Winfield Solutions, York, PA). Treatments included varying carrier water pH levels of 5, 6, 7, 8, or 9. The pH treatments were created by using organic pH buffer salts at 0.1 M. Water pH 5 and 6 were created with potassium hydrogen phthalate (Acros Organics, Geel, Belgium) and potassium phosphate monobasic salt (Avantor Performance Materials Inc., Phillipsburg, NJ) and titrated to the proper level with hydrochloric acid (HCl 37%, Mallinckrodt Baker, Dublin, Ireland) or sodium hydroxide (NaOH pellets, Mallinckrodt Baker). Deionized water was used to obtain water pH 7, whereas water pH 8 and 9 were created with Tris (hydroxymethyl) aminomethane (Acros Organics) and titrated to the proper level with 17 and 6 ml 0.1 HCL, respectively (Devkota and Johnson 2019; Roskamp et al. 2013). All solutions were tested just prior to application with a pH meter to ensure the desired pH levels.

To test the effect of carrier water hardness, imazapic was applied 35 DAP at 0.071 with 0.25% v/v NIS. Treatments included varying carrier water hardness levels of 0, 100, 200, 300, 400, and 500 mg L^{-1} equivalent of $CaCO_3$. Water hardness levels were adjusted using calcium chloride (Ca^{2+} dihydrate, granular, macron-fine chemicals; Avantor Performance Materials, Inc., Center Valley, PA) and magnesium sulfate (Fisher Scientific, Pittsburgh, PA) in a 3:1 ratio (Devkota and Johnson 2019; Roskamp et al. 2013). Water samples were tested for desired hardness level using a hardness test kit (HACH, Loveland, Co).

Greenhouse Experiments

Studies were conducted under greenhouse conditions to determine the effect of carrier water pH and hardness on imazapic efficacy on sicklepod growth at different heights. The studies were conducted during spring 2023, and the greenhouse was maintained at minimum and maximum temperatures of 25 and 28 C, and supplemental lighting was used to provide a 16-h photoperiod. Sicklepod seeds were planted 1 cm deep on 28-cm-wide and 53-cm-long seed trays at weekly intervals to obtain seedlings with varying sizes/heights. Seedlings were transplanted into 7.6-cm-wide by 6.4-cm-deep nursery pots at the one to two true-leaf stages (5 cm height). Seedlings were watered daily and fertilized weekly with Miracle-Gro® water-soluble all-purpose plant food (24-8-16; Scotts Miracle-Gro Products Inc., Marysville, OH).

The study consisted of two separate experiments (carrier water pH and carrier water hardness). In the carrier water pH experiment, treatments consisted of a two-way factorial of sicklepod height (10 cm, 15 cm, or 20 cm) and carrier water pH (5, 6, 7, 8, or 9). In the carrier water hardness experiment, treatments consisted of a two-way factorial of sicklepod height (10 cm, 15 cm, or 20 cm) and carrier water hardness (0, 100, 200, 400, and 800 mg L^{-1} equivalent of $CaCO_3$). Water pH and hardness solutions were created as they were for the field study. Imazapic was applied at 0.071 g ai ha^{-1} at the various pH and hardness levels with NIS 0.25% v/v. A nontreated check was included for treatment evaluation in both experiments. Sicklepod size was analyzed as the main effect in both experiments. The experiments were conducted in a randomized complete block design with five replications and repeated over time. Treatments were sprayed using a Research Track Sprayer at 140 L ha^{-1}, with a TeeJet TTI11002 nozzles traveling at 4.8 km h^{-1}.

Data Collection and Statistical Analysis

For the field experiments, a 1-m^2 area was marked with flags within each plot, and sicklepod plants were counted to record the initial density before treatment application in both years. After treatment application, percent weed control rating was recorded on a scale of 0% to 100% (where 0% is no injury and 100% is complete death of the plant). Control ratings on imazapic efficacy were recorded at 14 and 28 d after treatment (DAT) and the number of live sicklepod plants in the 1-m^2 marked area were counted at 28 DAT to record the final sicklepod density. Density reduction was determined by comparison of initial and final density and expressed as a percentage of density reduction. Aboveground sicklepod biomass was harvested at 28 DAP, dried at 60 C for 7 d, and dry weights were recorded.

For the greenhouse experiment, imazapic efficacy ratings were taken at 14 and 21 DAT, and plants were harvested at 21 DAT in a manner similar to that of the field experiments. Sicklepod control and biomass reduction was determined by comparison with the nontreated control and expressed as percentage control and biomass reduction. Data were subjected to ANOVA using the GLIMMIX procedure with SAS software (version 9.4; SAS Institute Inc. 2012) to indicate the effects of sicklepod size/height and carrier water pH and hardness. Initial analyses were performed on all dependent variables to determine the effect of year and experimental run as a fixed effect for the field and greenhouse experiments, respectively. Analyses showed the effect of year, experimental run, and treatments × year or experimental run interactions were not significant. Therefore, all subsequent analyses were performed for both years combined, and experimental runs combined as a random effect. Sicklepod control, density reduction, and biomass reduction data were arcsine square root–transformed. Significant means were separated using Tukey's honestly significant difference test at $P < 0.05$. After means separation, data were back transformed for reporting results as a percentage.

Results and Discussion

Field Experiments

Carrier pH

The effect of carrier water pH on imazapic efficacy for sicklepod control was not significant 14 DAT but control was influenced at 28 DAT (Table 1). Sicklepod control was significantly (9% to 13%) greater when imazapic was applied with water at pH 6, 7, or 8 compared with pH 5 or 9 (Table 1). Imazapic showed <70% reduction in sicklepod density per square meter when it was applied with water at pH 5, 6, or 9, and was lowest when imazapic was applied with water at pH 5, providing only 55% reduction compared with 81% and 77% reduction in sicklepod density with imazapic applied in carrier water at pH 7 and 8 (Table 1). Conversely, sicklepod biomass reduction was lowest (64%) when imazapic was applied with water at pH 9 (Table 1). No differences were observed among water pH 5, 6, 7, or 8 for sicklepod biomass reduction, which ranged from 84% to 93%. Peanut injury was minimal (≤5%) regardless of treatment, and only the nontreated produced a significant reduction in yield (Table 1). This was expected because the crop competed with the uncontrolled sicklepod and dramatically reduced harvest efficiency.

Generally, in terms of control or density and biomass reductions, both acidic (pH 5) and alkaline (pH 9) carrier water pH resulted in reduced imazapic efficacy for sicklepod control compared with deionized water at pH 7. Previous studies have shown that a higher or lower than optimum spray water pH may result in reduced solubility or rapid conversion of the herbicide to a less or nonactive degradative product, which subsequently affects herbicide absorption and translocation (Green and Cahill 2003; Roskamp et al. 2013; Sarmah and Sabadie 2002). Reduced efficacy of imazapic with acidic and alkaline pH water in the present study may be related to the effect of pH on solubility when mixing the herbicide, but we did not investigate it. However, visible differences in clarity of solution could be observed between the various pH levels immediately after mixing the herbicide (Figure 1). The pH of spray solution controls the ionic state and water solubility of weak-acid herbicides (Green and Hale 2005). When the pH is below the pKa, weak-acid herbicides have a neutral charge (un-ionized), and water solubility is low. When the pH increases above the pKa, weak-acid herbicides might have a positive charge with greater solubility, but they are ionic and thus difficult to penetrate the plant cuticle, which may be responsible for reduced efficacy at alkaline carrier water pH (Green and Hale 2005; Stirling 1994). Other studies have also reported reduced efficacy at alkaline pH for weak-acid herbicides such as mesotrione for horseweed control (Devkota et al. 2016), glufosinate for Palmer amaranth control (Devkota and Johnson 2016), and 2,4-D and premixed 2,4-D plus glyphosate for Palmer amaranth control (Devkota and Johnson 2019).

Carrier Water Hardness

Sicklepod control and density and biomass reductions with imazapic were not influenced by carrier water hardness at 14 and

Table 1. Effect of carrier water pH on sicklepod visible control at 14 and 28 d after treatment; sicklepod density and biomass reduction; peanut injury 28 d after treatment, and yield from imazapic in field experiments.[a,b,c]

	Control[d]					
Water pH	14 DAT	28 DAT	Density reduction[e]	Biomass reduction[f]	Peanut injury	Peanut yield
	%					kg ha^{-1}
5	64 a	79 b	55 c	84 a	5 a	3945 a
6	65 a	87 a	67 b	85 a	5 a	4453 a
7	74 a	86 a	81 a	90 a	4 a	4324 a
8	60 a	87 a	77 a	93 a	3 a	4468 a
9	65 a	77 b	62 b	64 b	4 a	4124 a
Nontreated control	–	–	–	–	–	2014 b
Pr > *F*	0.1	0.0003	0.001	0.009	0.2	0.05

[a] Abbreviation: DAT, days after treatment.

[b] Imazapic was applied 0.071 kg ai h^{-1} with 0.25% v/v nonionic surfactant.

[c] Means within a column and among carrier water pH or harness levels followed by the same letter are not significantly different based on adjusted Tukey's honestly significant difference test at $\alpha = 0.05$.

[d] Visible efficacy/injury from a 0% to 100% scale where 0% = no control/no injury and 100% = complete control/plant death.

[e] Density reduction was determined by comparison of initial and final density and expressed as a percentage of density reduction.

[f] Biomass reduction was calculated by subtracting dry weight of each treatment from nontreated control (225 g m^{-2}) and converting it to percentage of the nontreated check.

Figure 1. Visible observation of solubility of imazapic + nonionic surfactant at different carrier water pH levels.

28 DAT (Table 2). Regardless of the hardness level of the carrier water (0, 100, 200, 300, or 500 ppm), imazapic provided 64% to 76%, and 80% to 92% control of sicklepod at 14 and 28 DAT, respectively (Table 2). This indicated that carrier water hardness ≤500 ppm did not reduce imazapic efficacy for sicklepod control compared with deionized water. Imazapic treatment in this study included 0.25% v/v NIS, which might have prevented hard water antagonism of calcium and magnesium cations, as was reported in previous studies with glyphosate (Zollinger et al. 2013) and 2,4-D amine (Nalewaja et al. 1991), which are also weak-acid herbicides. Addition of NIS to weak-acid herbicides has been shown to overcome hard water antagonism by facilitating absorption as a solubilizer or partitioning sink for the herbicides (Nalewaja et al. 1991), which could explain the lack of differences between hardness treatments in the present study. Similar to the present findings, Mohoney et al. (2014) reported that carrier water hardness had a negligible overall effect on the efficacy of glyphosate on common ragweed (*Ambrosia artemisiifolia* L.), large crabgrass (*Digitaria sanguinalis* Cyperales), and pigweed species in corn crops (*Zea mays* L.).

Previous studies have shown that imazapic exhibits excellent safety to peanut (Dotray et al. 2001; Faircloth and Prostko 2010; Grichar et al. 2012), and the result of this study indicates that peanut tolerance to imazapic is not influenced by carrier water pH or hardness. Injury to peanut was minimal (≤5%), and only the nontreated plants exhibited a reduction in yield (Table 2). These results are similar to the findings reported by Mohoney et al. (2014) that crop injury from glyphosate was not affected by carrier water hardness when applied to corn. Although imazapic efficacy on sicklepod was lower at acidic and alkaline pH, the effect was not enough to reduce peanut yield. Carrier water hardness had no effect on sicklepod control and did not affect peanut yield. These results are similar to those reported by Mohoney et al. (2014), who observed no differences in yield when glyphosate was applied with hard water compared with distilled water as the spray carrier.

Greenhouse Experiments

Carrier Water pH

Sicklepod height and carrier water pH significantly ($P < 0.0001$) affected sicklepod visible control from imazapic, and there was a significant interaction ($P = 0.006$) of sicklepod height and carrier water pH for sicklepod control (Table 3). There was no carrier water pH effect ($P = 0.07$) or sicklepod height-by-carrier water pH interaction ($P = 0.4$) on sicklepod biomass reduction; however, the main effect of sicklepod height ($P = 0.016$) was significant at 3 wk after treatment. Imazapic applied to 10-cm-tall sicklepod provided 86% to 96% control, and control did not differ among carrier water pH levels (pH 5 to 9); however, when applied to 15- and 20-cm-tall sicklepod, control varied significantly with carrier water pH (Table 3). This indicates that the effect of carrier pH on the efficacy of imazapic for sicklepod control is dependent on sicklepod height at application. The effect of carrier water pH was previously shown to vary with herbicide, adjuvant, spray volume, and application rate (Daramola et al. 2022; Devkota and Johnson 2016; Matocha et al. 2006), and now weed size. Control of 15-cm-tall sicklepod was 25% greater with imazapic applied with acidic carrier water (pH 5) compared with alkaline carrier water (pH 9). Similarly, imazapic applied to 20-cm-tall sicklepod with acidic (pH 5 or 6) or neutral carrier water pH resulted in at least 30% to 35% greater control compared with alkaline carrier water pH 9 (Table 4).

Greater activity of imazapic on smaller compared with larger sicklepod plants may be attributed to the potential of young plants to absorb more herbicide than more matured plants (Penner 1989). Additionally, reduced plant vigor and lack of fully developed cuticles could have increased the sensitivity of smaller plants to the herbicide (Wyrill and Burnside 1976). Conversely, the herbicide degradation rate could be faster in older plants, thus allowing the

Table 2. Effect of carrier water hardness on sicklepod visible control at 14 and 28 d after treatment; sicklepod density and biomass reduction; peanut injury 28 d after treatment, and yield from imazapic in field experiments.[a–d]

	Control					
Water hardness	14 DAT	28 DAT	Density reduction[e]	Biomass reduction[f]	Peanut injury	Peanut yield
mg L^{-1} of $CaCO_3$	%					t ha^{-1}
0	72 a	83 a	71 a	96 a	5 a	4234 a
100	69 a	80 a	72 a	75 a	5 a	4354 a
200	76 a	92 a	78 a	93 a	4 a	4535 a
300	71 a	83 a	68 a	91 a	4 a	4256 a
400	73 a	88 a	78 a	89 a	4 a	4410 a
500	67 a	80 a	69 a	76 a	4 a	4532 a
Nontreated control	–	–	–	–	–	2132 b
Pr > *F*	0.5	0.06	0.7	0.1	0.6	0.03

[a] Abbreviation: DAT, days after treatment.

[b] Imazapic was applied 0.071 kg ai h^{-1} with 0.25% v/v nonionic surfactant.

[c] Means within a column and among carrier water pH or harness levels followed by the same letter are not significantly different based on adjusted Tukey's honestly significant difference test at $\alpha = 0.05$.

[d] Visible efficacy/injury from a 0% to 100% scale where 0% = no control/no injury and 100% = complete control/plant death.

[e] Density reduction was determined by comparison of initial and final density and expressed as a percentage of density reduction.

[f] Biomass reduction was calculated by subtracting dry weight of each treatment from nontreated control (225 g m^{-2}) and converting it to percentage of the nontreated check.

Table 3. Effect of carrier water pH on the efficacy of imazapic on visible control of sicklepod 28 d after treatment under greenhouse conditions.[a,b]

	Carrier water pH				
	5	6	7	8	9
Sicklepod height	Control				
cm			%		
5	96 a	93 a	89 ab	92 a	88 ab
10	80 bc	75 cd	69 cde	74 cde	64 de
15	64 de	67 de	63 e	62 e	44 f
Pr > *F*			0.001		

[a] Data were combined across experimental runs.

[b] Means within a column and among each factor levels followed by the same letter are not different based on adjusted Tukey's honestly significant difference test at $\alpha = 0.05$.

Table 4. Effect of plant size/height and carrier water hardness on the efficacy of imazapic on visual control and biomass reduction of sicklepod 28 d after treatment under greenhouse conditions.[a,b,c]

Treatments	Control[d]	Biomass reduction[e]
	%	
Sicklepod height		
cm		
5	81 a	74 a
10	67 b	64 b
15	58 c	56 c
Pr > *F*	<0.0001	<0.0001
Water hardness		
mg L^{-1} of $CaCO_3$		
0	73 a	67 a
100	72 a	68 a
200	65 ab	70 a
400	69 ab	71 a
800	62 b	55 b
Pr > *F*	0.003	0.002

[a] Imazapic was applied 0.071 kg ai ha^{-1} with 0.25% v/v nonionic surfactant.

[b] Data were combined across experimental runs.

[c] Means within a column and among carrier water pH or harness levels followed by the same letter are not significantly different based on adjusted Tukey at $\alpha = 0.05$.

[d] Visual efficacy/injury from a 0% to 100% scale where 0% = no control/no injury and 100 = complete control/plant death.

[e] Biomass reduction was calculated by subtracting the dry weight of each treatment from the nontreated control (9.6 g $plant^{-1}$) and converting it to percentage of the nontreated check.

plants to accumulate more biomass after herbicide application, although at a slower rate (Singh and Singh 2004). The results from this study agree with those from previous studies that reported reduced herbicide efficacy with increased plant heights (Barnes et al. 2020; Chahal et al. 2011; Corbett et al. 2004; Lancaster 2007; Meyer and Norsworthy 2019; Wehtje et al. 2000). Wehtje et al. (2000) reported that efficacy of imazapic was greater on Florida beggarweed at the unifoliate leaf stage than trifoliate leaf stage. Corbett et al. (2004) observed that the efficacy of bromoxynil and glyphosate on sicklepod decreased as the plants grew taller. Similarly, the efficacy of glyphosate was lower when it was applied to sicklepod at the 6-leaf stage compared with the 4-leaf stage (Singh and Singh 2004).

Although water solubility of weak-acid herbicides is generally low at acidic compared to alkaline water pH, uptake through the leaf cuticle is generally greater with acidic carrier water pH due to a higher proportion of the molecules being present in an undissociated form (Liu 2002; Matocha et al. 2006), which may explain the greater sicklepod control with imazapic the carrier water pH was acidic. Similar to the result of this study, Devkota and Johnson (2020) reported greater control of common lambsquarters (*Chenopodium album* L.), common ragweed, giant ragweed, horseweed, Palmer amaranth, and pitted morningglory (*Ipomoea lacunosa* Solanales) with dicamba and glyphosate when applied with acidic (pH 4) compared to alkaline (pH 9) carrier water. Likewise, Green and Hale (2005), reported that the addition of 1% wt/wt H_3PO_4 (acid) to acifluorfen and bentazon increased the activity of the herbicides on velvetleaf (*Abutilon theophrasti* L.) compared with the addition of 1% wt/wt K_3PO_4 (base), indicating increased efficacy at acidic compared to alkaline spray solution. Conversely, Liu et al. (2002) reported greater uptake of bentazon by white mustard (*Sinapis alba* L.) and wheat (*Triticum aestivum* L.) with an alkaline (pH 9) compared to an acidic (pH 5) spray solution.

Carrier Water Hardness

The main effects of sicklepod height and carrier water hardness on sicklepod control ($P < 0.0001$, and $P = 0.003$) and biomass reduction ($P < 0.0001$, and $P = 0.002$) with imazapic was significant (Table 4). There was no sicklepod height-by-carrier water hardness interaction for sicklepod control and biomass reduction. Similar to the carrier water pH experiment, efficacy of imazapic was lower with increasing sicklepod height, averaged across carrier water hardness levels (Table 4). Imazapic provided 81% control and 73% biomass reduction of 10-cm-tall sicklepod, whereas control and biomass reduction was at least 15% lower when applied to 15- or 20-cm-tall sicklepod when evaluated 3 wk after treatment (Table 4).

No differences were observed among carrier water hardness 0 to 400 mg L^{-1} of $CaCO_3$ equivalent for sicklepod control (62% to 73%) and biomass reduction (55% to 72%) (Table 4). This response is similar to the results observed in field experiments with carrier water hardness 0 to 500 mg L^{-1}, and agrees with results reported by Schortgen and Patton (2020) that horseweed biomass reduction with 2,4-D dimethylamine was not influenced by water hardness ranging from 75 to 300 mg $CaCO_3$ L^{-1}. However, in the present study, sicklepod control and biomass reduction was 15% and 17% lower, respectively, with carrier water harness 800 mg $CaCO_3$ L^{-1} compared with 0 mg L^{-1} (Table 4). Similar to the results of this study, Devkota and Johnson (2019) reported at least 10% reduction in common lambsquarters, Palmer amaranth, and pitted morningglory control with 800 mg $CaCO_3$ L^{-1} carrier hardness compared with 0 mg L^{-1} with dicamba and glyphosate. Schortgen and Patton (2020) also observed reduced 2,4-D efficacy on horseweed with carrier water hardness 600 mg $CaCO_3$ L^{-1} compared with water hardness 0 to 300 mg $CaCO_3$ L^{-1}.

Practical Implications

The results of this study showed that carrier water pH and hardness have the potential to affect imazapic efficacy for sicklepod control. The efficacy of imazapic on sicklepod was negatively affected by both acidic (pH 5) and alkaline (pH 9) carrier water when applied to plants that were 5 cm to 30 cm tall in a field experiment. However, the greenhouse experiment showed that the effect of carrier water pH on sicklepod control with imazapic was dependent on plant size. Although no differences were observed between acidic (pH 5 and 6), alkaline (pH 8 and 9), or neutral (pH 7) carrier water for the control of 10-cm-tall sicklepod with imazapic in the greenhouse experiment, reduced efficacy is more likely to be observed with alkaline carrier water (pH 9) when imazapic is applied to larger sicklepod (>10 cm height). This suggests the need for a timely application for effective control. In addition, the greenhouse experiment showed that the control of larger sicklepod (15 to 20 cm tall) with imazapic was significantly improved with carrier water pH 5 compared with pH 9. This suggest that acidic carrier water pH is favorable for sicklepod control with imazapic, similar to that of acifluorfen and bentazon, which provided greater control of velvetleaf (*Abutilon theophrasti* L.) with acidic compared to alkaline carrier water pH (Matocha et al. 2006).

Results of the field experiment showed that carrier water hardness ≤500 ppm did not reduce imazapic efficacy for sicklepod control compared with deionized water, which suggest that carrier water hardness within this range may not be a factor of concern for imazapic efficacy when applied with NIS. However, results from the greenhouse experiment showed that carrier water hardness up to 800 mg L^{-1} equivalent of $CaCO_3$ L^{-1} can potentially reduce sicklepod control with imazapic and should be avoided or amended with water-conditioning agents for increased efficacy. Although the effects of carrier water pH and hardness on imazapic efficacy did not compromise peanut yield in the present study, optimizing efficacy for weed control through appropriate carrier water pH and harness is important to reduce weed population.

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