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Imazaquin Spray Retention, Foliar Washoff and Runoff Losses under Simulated Rainfall

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Abstract: Spray retention and foliar washoff of imazaquin in smooth pigweed (*Amaranthus hybridus* L.) and sicklepod (*Senna obtusifolia* (L.) Irwin and Barneby) were investigated. Imazaquin (70 g AI ha^{-1}) was applied alone, with nonionic surfactant 'X-77' or organosilicone-based nonionic surfactant 'Kinetic' to plants at two- to five-leaf stage and subjected to 2·5 cm rainfall in 20 min either 1 or 24 h after application. Imazaquin spray retention was higher with adjuvants than without. Retention was similar between adjuvants in smooth pigweed but 'Kinetic' retained twice as much imazaquin as 'X-77' in sicklepod. Rainfall 1 h after application washed off three-quarters of foliar residues regardless of plant species or adjuvant. However, at 24 h after application, foliar washoff was lowest with 'Kinetic' followed by 'X-77' in both species. Imazaquin washoff ranged from 33 to 88% in the two species at 24 h after application. Overall, imazaquin activity was similar with either adjuvant in smooth pigweed but 'Kinetic' was more effective than 'X-77' in sicklepod. Runoff losses from the surface of a Bosket sandy loam (Mollic Hapludalfs) soil in runoff trays (1·2% slope) were also studied. Imazaquin was applied as above to trays with and without smooth pigweed canopy. A 2·5-cm rainfall was applied in 20 min at 24 h after application. Runoff samples collected in one-litre fractions were analyzed by enzyme-linked immunosorbent assay. Sediment (but not water) in runoff was greatly reduced (56%) by pigweed cover as compared to bare trays. Imazaquin in the first litre of runoff was higher than in subsequent runoff fractions regardless of pigweed cover. Total imazaquin lost in runoff was higher in pigweed cover (23%) than bare trays (16% of applied). Imazaquin concentration in 10–20 cm soil depth in pigweed cover trays was higher than in bare trays. These results suggest that imazaquin is vulnerable to foliar washoff and the herbicide washed off could move in the aqueous phase due to shorter contact time with soil for sorption.

Key words: imazaquin, adjuvant, rainfall, runoff, spray retention, foliar washoff

1 INTRODUCTION

Imazaquin, an imidazolinone herbicide, is used for control of several annual grasses and broadleaf weeds in soybean (*Glycine max* (L.) Merr.). It is applied either to the surface of the soil or to plant foliage. Imazaquin has a water solubility of 60 mg litre^{-1} and an octanol–water partition coefficient (K_{ow}) of 2·2.[1] It has an ionizable carboxyl group with a pK_a of 3·8.[1] Consequently, imazaquin exists predominantly in the anionic form at near-neutral soil pH and most likely partitions into the aqueous phase.

Rainfall can reduce the efficacy of foliar-applied herbicides by washing them off the foliage.[2,3] Herbicide washed off foliage during rainfall, in addition to any herbicide spray not intercepted by foliage, would land on the soil, where it would be subjected to the same environmental fate as soil-applied herbicide (Fig. 1). In soil, herbicide exists in dynamic equilibrium between solution and adsorbed states. Removal of herbicide in soil can occur *via* several processes, including surface runoff and leaching (Fig. 1). Organosilicone adjuvants are a newer class of adjuvants which increase the effi-

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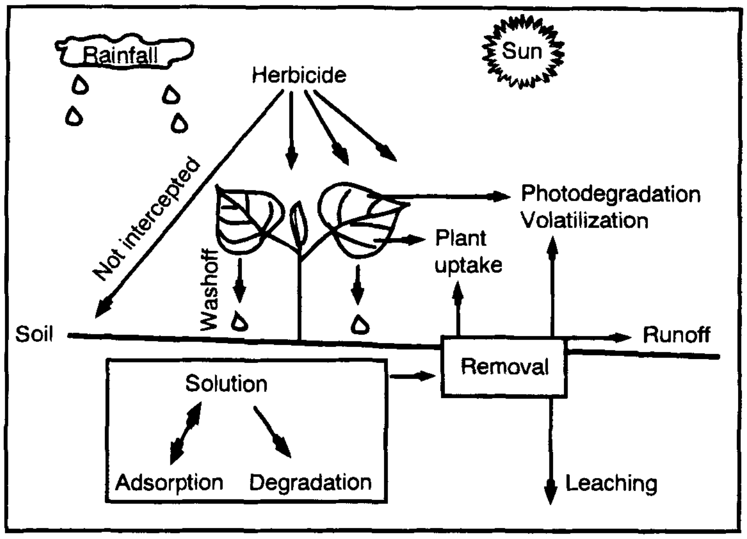

Fig. 1. Environmental fate of foliar-applied herbicides.

cacy and provide rainfastness of several herbicides in plant species.[4–7] 'Kinetic' (KIN; an organosilicone-based proprietary blend of polyalkyleneoxide-modified polydimethylsiloxane and nonionic surfactants, Helena Chemical Company, Memphis, TN 38119.) increased bentazone retention on foliage of several weed species, thus reducing the amount of herbicide reaching the soil.[3] Rainfall can also cause pesticide runoff and leaching when applied to soil.[8–15] However, in some cases, moderate rainfall immediately after application of certain soil-applied herbicides is beneficial for herbicide incorporation into the upper soil zone. The elapsed time between pesticide application and a rainfall event can be critical to pesticide washoff, runoff or leaching losses.

Knowledge of herbicide foliar washoff and runoff loss is essential information for environmental modeling, optimizing weed management and in developing alternative production practices.[16] Although information on adjuvant-enhanced efficacy of imazaquin is reported in literature,[17,18] imazaquin spray retention on foliage and foliar washoff by rainfall is not well documented. The objectives of this study were to (1) quantify spray retention on foliage and the extent of foliar washoff of imazaquin applied with 'Valent X-77 spreader' (X-77; a mixture of alkyarylpolyoxyethylene glycols, free fatty acids and isopropanol, Valent USA Corporation, Walnut Creek, CA 94596.) or KIN adjuvant in smooth pigweed (susceptible) and sicklepod (tolerant) weed species and (2) quantify runoff loss of imazaquin in the presence or absence of smooth pigweed canopy cover.

2 MATERIALS AND METHODS

2.1 Adjuvant and rainfall effects on imazaquin activity

Smooth pigweed (*Amaranthus hybridus* L.) and sicklepod (*Senna obtusifolia* (L.) Irwin & Barneby) plants were grown in 10-cm diameter by 9-cm deep plastic pots containing a mixture of Bosket sandy loam soil (fine-loamy, mixed, thermic Mollic Hapludalfs: 43% sand, 48% silt, 9% clay, 1·51% organic matter, 5·45 pH) and 'Jiffy mix' (Jiffy Products of America Inc., Batavia, IL 60510) at 1 + 1 by volume). After emergence, seedlings were thinned to two per pot. Plants were grown in the greenhouse at a 35/27°C mean day/night temperature and natural light with a 14-h photoperiod. Plants were watered and fertilized as needed. Treatments consisted of imazaquin ('Scepter'® 1.5 AS) at 70 g AI ha^{-1} alone, with X-77 (2·5 ml $litre^{-1}$) and with KIN (2·5 ml $litre^{-1}$). X-77 was included as a reference surfactant to compare any potential benefits of KIN, a newer class of organosilicone adjuvant is claimed to increase the efficacy and rainfastness of specific herbicides in certain plant species. The rates selected for adjuvants were within the range of normal use rates. Sicklepod and smooth pigweed plants were treated at the two- to three-leaf and five- to six-leaf stages, respectively. Spray solutions were applied using an indoor spray chamber equipped with an air-pressurized spray system in a volume of 187 litre ha^{-1} at 138 kPa using TeeJet 8002E (Spraying Systems Company, Wheaton, IL 60189) nozzles.

Effect of simulated rainfall on imazaquin activity was evaluated by applying 2·5 cm water at 7·5 cm h^{-1} intensity. A treatment with no simulated rainfall was included as a control. The rainfall simulator, similar to one described by Meyer and Harmon,[19] produced droplet size, fall velocity and kinetic characteristics of natural rainstorms. It was set to deliver droplets at 3·0 m height and the actual amount of rainfall was measured at the plant level with rain gauges. Simulated rainfall was applied at 0·5, 1, 4, 8, 24 and 96 h after application of imazaquin. Since imazaquin also has soil activity, the soil in the pots was covered with activated charcoal (Sigma Chemical Company, St. Louis, MO

63178) before herbicide application to confine herbicidal activity to the foliage. The charcoal was removed after rainfall application. Imazaquin activity was assessed two weeks after treatment by recording shoot fresh weight. Data were expressed as percentage shoot fresh weight reduction (i.e. control) as compared to untreated plants. The experiment was conducted in a split-plot design with adjuvants as main plots and rainfall as subplots. Treatments were replicated four times and the experiment was repeated. Data were subjected to combined analysis of variance and means were separated at the 5% level of significance by Fisher's LSD test.

2.2 Imazaquin foliar washoff

Plants were treated with herbicide and subjected to simulated rainfall as described in the above study, except that one plant per pot was used. Immediately after rainfall application, plants were excised at the soil surface and placed in 1-litre glass bottles. Methylene chloride (100 ml) was added and the bottles thoroughly shaken for 1 min. Plants were removed from the bottles and extracted twice more with methylene chloride (50 ml, 15 s). The extracts were stored at 2°C and processed within one week. Methylene chloride extracts were filtered (Whatman #1) into a round-bottom flask and evaporated to dryness at 40°C on a rotary evaporator. The residue was dissolved in methanol (4 ml) and imazaquin was analyzed by high-pressure liquid chromatography (HPLC; Waters Corporation, Milford, MA 01757). Imazaquin peak separation was achieved using an Adsorbosphere (C_{18}) column (Alltech Associates Inc., Deerfield, IL 60015) and gradient mobile phase conditions. The initial mobile phase conditions were water (pH 3·0 with H_3PO_4) + acetonitrile (55 + 45 by volume) at a flow rate of 1 ml min^{-1}, with a gradient change to 100% acetonitrile over 23 min. Imazaquin was monitored at 240 nm wavelength using an UV detector (Model 490, Waters Corporation, Milford, MA 01757). Imazaquin recovery from plants was 89($\pm$ 3)%. Percentage increase in spray retention with adjuvants over no adjuvant control was calculated only for plants receiving no rainfall at 1 h after application of imazaquin. Percentage of foliar washoff by rain at 1 or 24 h after imazaquin application as compared to the no rainfall control was calculated as means of eight replications.

2.3 Surface tension and contact angle

Surface tension of imazaquin and adjuvant solutions was determined using SensaDyne Surface Tensiometer (Chem-Dyne Research Corporation, Mesa, AZ 85275), Model 6000. The contact angle of a 1-μl droplet on the leaf surface was measured with NRL C.A. Goniometer (Rame-hart Inc., Mountain Lakes, NJ 07046), Model 100-00 115.

2.4 Imazaquin runoff study

Runoff trays used in the studies were described previously by Wauchope.[20] Briefly, fiberglass trays were 2·24 m long, 1·22 m wide and 0·25 m deep with impermeable bottoms. One end of the tray provided a lip over which runoff water flowed into a sloped-floor trough containing a drain tube at the lower end. The trays were supported on concrete block pedestals 30 cm high and were adjusted to 1·2% slope. The soil used in the study was a Bosket sandy loam. Trays were filled with soil to 23 cm depth and soil surface was leveled by raking. Four trays were planted with smooth pigweed to simulate weed canopy and four trays were kept bare.

Imazaquin at 70 g AI ha^{-1} with X-77 or KIN at 2·5 ml $litre^{-1}$ was applied to the surface of the soil in bare trays and to foliage in smooth pigweed trays. Smooth pigweed plants were 8–10 cm tall with a complete coverage of ground at spraying. There were two trays with and two without pigweed canopy cover for each of the imazaquin treatments. A tractor-mounted sprayer system equipped with Teejet 8002E-SS nozzles was used to apply treatments in a spray volume of 187 litre ha^{-1} at 179 kPa. Three 9-cm Petri dishes were placed diagonally at the surface of soil in bare trays and at the level of foliage in pigweed trays to collect spray to determine the actual amount of herbicide applied. Rainfall (2·5 cm applied at an intensity of $\approx$ 7·5 cm h^{-1}) was applied 24 h after herbicide application. Rainfall was applied to one tray at a time and runoff (both water and sediment) was collected in one-litre fractions. Glass collection bottles were weighed before and after runoff collection. Bulk runoff samples were stored at 0–2°C and subsamples for herbicide analysis were frozen. The subsamples were processed within seven to eight weeks.

Petri dishes used to collect imazaquin spray were rinsed with methanol (8 ml) and the washings analyzed by HPLC as described above. Sediment was determined from every runoff fraction. Total sediment was determined by transferring an aliquot (200 ml) of well-shaken runoff into a weighed beaker and weighing the residue remaining in the beaker after oven drying. Imazaquin residue was determined from every other runoff fraction starting from the first. The EnviroGard imazapyr plate kits (Millipore Corporation, Bedford, MA 01730) were used for the immunoassay analysis of imazaquin in runoff samples. The EnviroGard imazapyr plate kit will not differentiate between imazapyr and other imidazolinone herbicides such as imazaquin. The kits use polyclonal antibodies coated to the walls of the test wells. The runoff sample (100 μl) was added to each antibody-coated well. After reaction of imazapyr-enzyme conjugate (100 μl) and substrate (100 μl), the wells were scanned using a Microplate spectrophotometer (Bio-Tek Instruments, Winooski, VT 05404) at 450 nm. Imazaquin concentration in samples was calculated from a standard curve.

Soil samples were collected from the 0–10 and 10–20 cm depths of the runoff trays, 24 h after simulated rainfall (48 h after imazaquin application) to assess the downward movement of the herbicide. Imazaquin was extracted from the soil by shaking 85 g (oven-dry equivalent) field moist soil with 90% methanol (100 ml) for 1 h on a reciprocal shaker. The slurry was centrifuged for 10 min at 4080*g* and the supernatant decanted. The extraction was repeated with 90% methanol (2 × 60 ml), and the three extracts were combined. Extracts were vacuum-filtered through Whatman GF/D glass fibre paper (Whatman LabSales, Hillsboro, OR 97123) to remove sediment. The extracts were stored at 2°C and processed within one week. Methanol was evaporated completely in a round-bottom flask at 40°C on a rotary evaporator. The volume of the water remaining in the flask was measured and an aliquot was filtered using Acrodisc 0·2 μm (Gelman Sciences, Ann Arbor, MI 48106) into a vial for imazaquin analysis by HPLC as described above. The extraction recovery of imazaquin was 70(± 5)%.

3 RESULTS AND DISCUSSION

3.1 Imazaquin spray retention and foliar washoff

In the absence of rainfall, imazaquin foliar residues on both species were higher on plants treated with adjuvants than with no adjuvant at 1 and 24 h after application (Tables 1 and 2). Overall, imazaquin residues retained on the canopy of smooth pigweed were higher than on sicklepod canopy for the respective treatments at 1 and 24 h after application. Imazaquin residues on plants ranged from 7·7(±0·7) to 17·7(±1·4) $\mu g\ g^{-1}$ plant in smooth pigweed and from 1·1(±0·1) to 17·0(±2·6) $\mu g\ g^{-1}$ plant in sicklepod at 1 h after application (Table 1). Differences in the quantities deposited on the foliage between the weed species were primarily due to differences in plant size (Fresh weight: 1·8 g per plant in smooth pigweed versus 1·1 g per plant in sicklepod) and leaf surface characteristics (see Section 3.2). This trend is similar to that observed for bentazone retention by these two species.[3] In general, differences between adjuvants in retention of imazaquin by foliage were more apparent in sicklepod (tolerant species) than in smooth pigweed (susceptible species). In sicklepod, KIN increased retention of imazaquin spray by 16-fold as compared to 8-fold by X-77 over no-adjuvant control at 1 h after application (Table 1). However, in smooth pigweed, the increase in imazaquin spray retention was rather similar between X-77 (143%) and KIN (130%). At 24 h after application, imazaquin residue on foliage in general was lower than at 1 h after application, partly due to volatilization, photodegradation or plant uptake and metabolism. In addition, plant growth during the 24-h period may have also contributed to lower imazaquin residue per unit plant weight. Plant weight of smooth pigweed was 2·1 and 1·8 g per plant and of sicklepod was 1·3 and 1·1 g per plant, respectively, at 24 and 1 h after application.

A simulated rainfall of 2·5 cm applied at 1 h after herbicide application washed off most of the imazaquin residue from foliage (Table 1). Foliar washoff within a species was similar, regardless of adjuvants, at 1 h after application. At 24 h after application, foliar washoff was

TABLE 1
Imazaquin Residue and Foliar Washoff from Plant Canopy at 1 h after Imazaquin Application with Adjuvants

Weed species	*Adjuvant*	*Imazaquin residue on canopy ($\mu g\ g^{-1}$ plant)* No rain[a]		*Imazaquin residue on canopy* Rain	*Imazaquin foliar washoff (%)*[b]
Smooth pigweed	No adjuvant	7·7		1·2	87a
	X-77	18·7 (143)		3·3	82a
	KIN	17·7 (130)		2·8	84a
	LSD (0·05)[c]		3·2		
Sicklepod	No adjuvant	1·1		0·2	78a
	X-77	8·2 (661)		2·3	67a
	KIN	17·0 (1469)		3·5	76a
	LSD (0·05)[c]		3·6		

[a] Values in parentheses indicate percentage increase in spray retention of imazaquin with adjuvants over no adjuvants.
[b] Percentage of imazaquin washed off by rain 1 h after imazaquin treatment, as compared to the no-rain control. Value is a mean of eight replications. Means within a column for each species followed by the same letter are not significantly different at the 5% level as determined by Fisher's LSD test.
[c] LSD for comparing means of adjuvant × rain interaction within each species.

TABLE 2
Imazaquin Residue and Foliar Washoff from Plant Canopy at 24 h after Imazaquin Application with Adjuvants

Weed species	*Adjuvant*	*Imazaquin residue on canopy ($\mu g\ g^{-1}$ plant)* No rain		*Rain*	*Imazaquin foliar washoff (%)*[a]
Smooth pigweed	No adjuvant	5·1		0·6	88a
	X-77	9·3		3·3	62b
	KIN	9·0		3·7	57b
	LSD (0·05)[b]		1·8		
Sicklepod	No adjuvant	0·7		0·2	70a
	X-77	4·1		1·7	56ab
	KIN	6·6		4·9	33b
	LSD (0·05)[b]		1·8		

[a] Percentage of imazaquin washed off by rain 24 h after imazaquin treatment, as compared to the no-rain control. Value is a mean of eight replications. Means within a column for each species followed by the same letter are not significantly different at the 5% level as determined by Fisher's LSD test.
[b] LSD for comparing means of adjuvant × rain interaction within each species.

higher without adjuvant than with adjuvants in both species (Table 2). However, the extent of imazaquin residue washed off from the foliage by rainfall within a weed species was relatively similar for both adjuvants (Tables 1 and 2). These results are similar to the range reported for other pesticides. For example, a rainfall of 2·5 cm applied 1 h after application washed off 39–98% of lactofen and bentazone in several weed species.[2,3] In other studies, a rainfall of 2·4 to 11·1 cm applied 2 h after application washed off 46–55% of permethrin,[21,22] 62% of malathion,[22] 62% of EPN and 88% of parathion-methyl[23] from plant foliage.

Rainfall 1 h after application simulated conditions where the maximum amount of imazaquin would be susceptible to washoff. Rainfall 24 h after application simulated a field condition when herbicide application occurs on a dry day, but a rainfall is encountered the following day. These two simulated conditions allowed us to estimate the extent of imazaquin washoff from foliage. Our studies suggest that in the event of high intensity rainfall occurring within a few hours of application, a considerable amount of imazaquin would wash off from foliage onto the soil, in addition to any imazaquin not intercepted by foliage at the time of herbicide application. In the event of rainfall occurring 24 h after imazaquin application, imazaquin remaining on plant foliage would also be susceptible to washoff.

3.2 Adjuvant and rainfall effects on imazaquin activity

Shoot fresh weight reduction was generally higher in smooth pigweed (susceptible) than in sicklepod (tolerant) regardless of adjuvant and rainfall (Fig. 2). However, adjuvant and rainfall effects were more apparent in sicklepod than in smooth pigweed (Fig. 2). In smooth pigweed, rainfall applied within 24 h after application of imazaquin without adjuvant reduced the activity, whereas both adjuvants maintained activity regardless of time of rainfall application. However, in sicklepod, simulated rainfall reduced imazaquin activity regardless of adjuvant, and rainfall within 24 h after imazaquin application resulted in loss of activity as

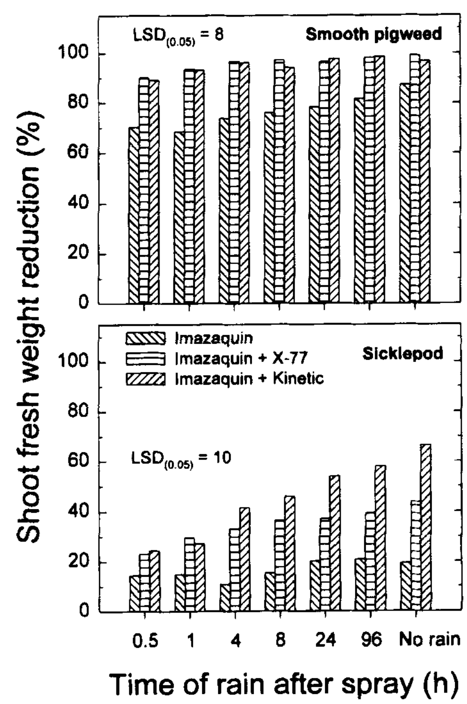

Fig. 2. Adjuvant and rainfall effects on imazaquin activity in smooth pigweed and sicklepod. Shoot fresh weight recorded two weeks after herbicide treatment. LSD for comparing interaction means of adjuvant and rainfall.

compared to no rainfall controls. Overall, inclusion of KIN reduced shoot fresh weight more than X-77 (Fig. 2). Simulated rainfall within 4–24 h after application of several herbicides such as clopyralid, dicamba, glyphosate, picloram, triclopyr and bentazone has been shown to result in partial or complete loss of herbicidal activity.[3,5,24,25] However, adjuvant efficacy can be weed-species specific.[3,5,7] In smooth pigweed, similarity of imazaquin activity between the adjuvants was most likely due to the equivalent amounts of imazaquin retained by either adjuvant (Tables 1 and 2), whereas increased imazaquin activity with KIN over X-77 in sicklepod was partially attributed to higher imazaquin retained in KIN treatments (Tables 1 and 2). Similarly, KIN and the organosilicone adjuvant 'Sylgard 309' (Dow Corning Corporation, Midland, MI 48686) were reported to be effective in maintaining glyphosate, acifluorfen and bentazone activity in several weed species when subjected to rainfall after herbicide application.[3,5,7]

Since imazaquin is absorbed both by roots and foliage, any herbicide reaching the soil is potentially available for root uptake. Malefyt and Quakenbush[18] have examined the effect of rainfall on the activity of foliar-applied imazaquin with and without root uptake. They observed that rainfall received any time during the first 24 h after imazaquin application decreased control of sicklepod from 85% to 25% when root uptake of imazaquin washed off from foliage was prevented. However, the same rainfall had a minimal effect on sicklepod control (95% with no rainfall versus 85% with rainfall) when root uptake of imazaquin washed off from foliage was not prevented. Under field conditions, therefore, light rainfall soon after foliar application may have minimal effects on the activity of imazaquin (root uptake not prevented), except in plant species which absorb imazaquin primarily through foliage with very limited root uptake.

Differential responses to imazaquin between susceptible and tolerant weed species could be due to differences in spray solution characteristics between adjuvants, as well as leaf surface characteristics. Addition of adjuvants to the spray solutions reduced surface tension as compared to solutions without adjuvants and KIN was more effective than X-77 (Table 3). Decrease in surface tension results in smaller droplet size, thereby reducing contact angle of the impinging droplet, resulting in a better coverage of the spray.[26] Overall, contact angles of imazaquin solutions on the leaf surface were smaller (less repulsion) with KIN (15–20°) than with X-77 (37–51°) in the two species (Table 3). Repulsion usually indicates the presence of a smooth layer of wax on the leaf surface.[27] Contact angle of water on the leaf surface of smooth pigweed (susceptible species) was 81° as compared to total repulsion on sicklepod (tolerant species). Repulsion to a water droplet on sicklepod leaf has been reported by others.[3] Greater efficacy of imazaquin with KIN may be partially due to improved dispersion of spray solution on sicklepod leaves as compared to X-77. Spray retention in sicklepod was higher when KIN was included in the spray solution (Table 1). Solutions of the organosilicone adjuvant 'Silwet L-77' (Union Carbide Corporation, Research Triangle Park, NC 27709), also had higher spread coefficients than solutions of crop oil concentrate on johnsongrass (*Sorghum halepense* (L.) Pers.) leaves.[28] The enhancement of herbicide efficacy by organosilicone adjuvants has often been attributed to reduced surface tension and an associated increase in leaf wetting, spreading, cuticle penetration and promotion of stomatal infiltration, thus favoring rapid foliar uptake.[3,5,7,28–30]

3.3 Imazaquin runoff study

The interactions between adjuvant and pigweed cover as well as the main effect for adjuvants were not statistically significant, therefore, only the data for the main effect of pigweed cover are presented. Soil moisture in 0–5 cm depth at the time of imazaquin applica-

TABLE 3
Surface Tension and Contact Angle of Imazaquin and Adjuvant Solutions

Solution[a]	Surface tension ($mN\ m^{-1}$)	Contact angle on leaf surface (degree)	
		Smooth pigweed	Sicklepod
Water	72	81	R[b]
Imazaquin	65	68	R[b]
X-77	28	48	52
Imazaquin + X-77	28	37	51
KIN	20	13	17
Imazaquin + KIN	20	15	20

[a] Solutions were prepared with imazaquin at 70 g ha^{-1} in 187 litre ha^{-1}, X-77 at 2·5 ml $litre^{-1}$ and KIN at 2·5 ml $litre^{-1}$.
[b] Repulsion of 1-μl droplet.

tion was 15·1% in bare and 20·5% in pigweed cover trays. Runoff from bare trays was 34·8 litre $tray^{-1}$ as compared to 33·1 litre $tray^{-1}$ in pigweed cover trays (Table 4), or about one-half of rainfall applied was lost as runoff, regardless of pigweed cover. Time elapsed between onset of rainfall and beginning of runoff in trays was about 1 min regardless of pigweed cover. At this stage of plant growth, underneath the pigweed canopy, the soil surface had a limited thatch (stems, roots, and dead plant residue). As a result, total runoff was similar regardless of pigweed cover. However, the plant canopy was able to retard movement of sediment in runoff, possibly by reducing the impact of rain droplet, thus reducing erosive effect. Total sediment loss from pigweed cover trays (179 kg ha^{-1}) was lower than from bare trays (404 kg ha^{-1}), amounting to a 56% reduction by pigweed cover (Table 4). Sediment load ranged from 1·9 to 4·8 g $litre^{-1}$ in bare trays and from 0·9 to 2·9 g $litre^{-1}$ in weed cover trays (Fig. 3).

In bare trays 16% of applied imazaquin was lost in runoff, compared to 23% of that applied from cover crop trays (Table 4). Thus, there was 44% more imazaquin runoff loss under pigweed cover. Runoff losses observed in this study are slightly higher than the range reported for 2,4-D (1–10%),[9,10] atrazine (4–12%),[13] cyanazine and sulfometuron-methyl (1–3%),[15] fluometuron (1%),[2,8] lactofen (3%),[2] and norflurazon (2–4%)[2,31] under various conditions. In a review of pesticide losses in runoff from agricultural fields, Wauchope[11] concluded that, for most pesticides, the total losses were less than 0·5% of the amounts applied except for organochlorine insecticides where losses ranged from 1 to 5%, depending on the conditions. However, our study was designed to simulate a 'worst-case scenario'.

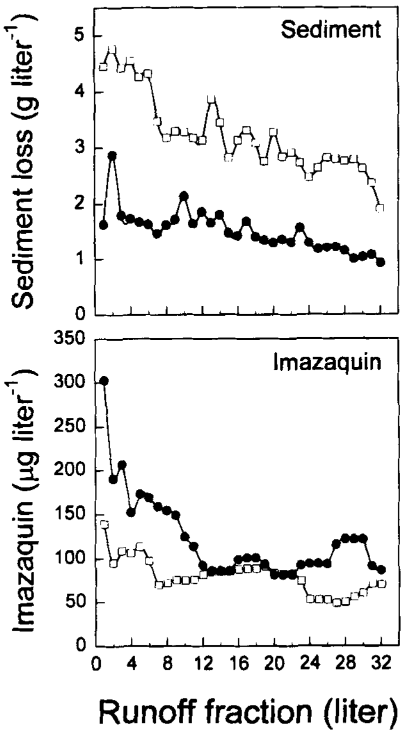

Fig. 3. Sediment loss and imazaquin concentration in runoff from (□) bare soil and (●) pigweed cover trays.

TABLE 4
Imazaquin Load and Runoff Losses from Bare soil and Smooth Pigweed Cover Trays

Variables	*Bare soil*[a]	*Pigweed cover*[a]	*t-test*[b]
Imazaquin applied[c]			
(mg per tray)	17·7 (0·5)	17·3 (1·1)	ns
(g ha^{-1})	64·8 (1·9)	63·3 (3·9)	ns
Rainfall			
Amount (cm)	2·5	2·5	ns
Intensity (cm h^{-1})	7·4 (0·02)	7·5 (0·01)	ns
Runoff volume			
(litre per tray)	34·8 (1·3)	33·1 (0·4)	ns
(as % of rainfall)	50·9 (1·9)	48·4 (0·6)	ns
Sediment loss			
(kg ha^{-1})	404·1 (62·4)	178·5 (8·6)	*
Imazaquin lost in runoff			
(mg per tray)	2·8 (0·2)	4·0 (0·07)	*
(as % of applied)	16·0 (1·7)	23·3 (1·3)	*
lost in first litre runoff			
(mg $litre^{-1}$)	0·1 (0·002)	0·3 (0·07)	*
(as % of applied)	0·8 (0·03)	1·7 (0·3)	*

[a] Standard errors in parentheses.
[b] ns = non-significant, * = significant at 5% level as determined by *t*-test.
[c] Imazaquin applied was determined from the herbicide spray collected in Petri dishes.

The first litre of runoff had the highest concentration of imazaquin, regardless of pigweed cover (303 μg litre^{-1} in pigweed cover versus 139 μg litre^{-1} in bare trays) with a gradual decrease in concentration in subsequent samples (Fig. 3). Similar patterns have been reported for 2,4-D,[9] atrazine,[13] cyanazine,[15] and lactofen, fluometuron and norflurazon.[2] The decrease in concentration can be partially attributed to herbicide leaching below the soil surface due to continuous rainfall (Fig. 4); consequently less chemical would be available for runoff. At 24 h after simulated rainfall, the imazaquin concentration in 0–10 cm soil depth was higher in bare trays as compared to pigweed cover trays (Fig. 4). However, concentration in 10–20 cm soil depth was higher for pigweed cover than in bare trays.

Overall, imazaquin concentration in runoff from pigweed cover trays was higher than in runoff from bare trays (Fig. 3). Reduced loss of imazaquin in runoff from bare trays may be due to herbicide sorption to soil. Herbicide applied to bare trays had a longer contact time (24 h) with soil before a rainfall application as opposed to pigweed cover trays where most of the herbicide had remained on the foliage until rainfall application. Results of the washoff study suggest that a 2·5 cm rainfall even 24 h after application can wash off 57–62% of imazaquin applied and thus imazaquin will be available for runoff and leaching (Table 2). Imazaquin (acid) is relatively water-soluble (60 mg litre^{-1}) and the ionic form would be even more water-soluble. In addition, imazaquin requires at least 4 h to reach sorption equilibrium.[32] As a result, imazaquin residue washed off from the foliage by a high-intensity rainfall (7·5 cm h^{-1}), would probably remain in the aqueous phase, owing to a shorter contact time with soil for sorption, and move with the surface runoff or leach. This reduced soil sorption of imazaquin explains observed higher concentrations in runoff samples (Fig. 3), higher loss in runoff (Table 4) and higher soil concentration in 10–20 cm soil depth (Fig. 4) of pigweed cover trays as compared to bare trays.

Under field conditions, ground cover with canopy can vary within and between fields. Canopy cover may vary from 0 to 100% depending upon weed species, density and growth. Under field conditions, it is difficult to quantify how much of imazaquin spray is intercepted by plant foliage due to variability in canopy cover. In this study, smooth pigweed cover trays had 100% canopy coverage, simulating maximum interception of herbicide spray, with little or none falling on the soil surface. The bare trays simulated the other extreme with all imazaquin spray contacting the soil surface. Typical imazaquin application in the field will fall between these extremes of canopy coverage. Imazaquin washed off from foliage during rainfall in addition to any herbicide spray not intercepted by foliage would reach the soil and be subjected to the environmental fate similar to that depicted in Fig. 1. Since imazaquin is readily absorbed by both roots and foliage, any herbicide washed off from foliage would be available to the plants through root uptake.

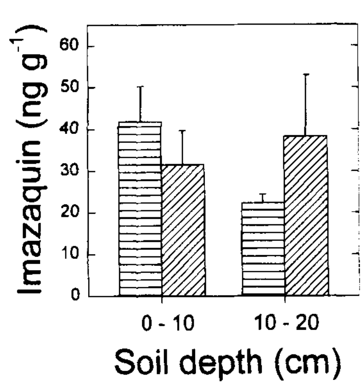

Fig. 4. Imazaquin concentration in 0–10 and 10–20 cm soil depths of (▤) bare soil and (▨) pigweed cover trays, at 24 h after rainfall application. Standard error bars are shown on each histogram.

4 CONCLUSIONS

These results suggest that adjuvants have the potential to increase herbicide spray retention on foliage, thus minimizing the amount of unintercepted spray reaching the soil. Imazaquin is vulnerable to foliar washoff, particularly in the event of a rainstorm occurring within 1 h of application. Even 24 h after application, a 2·5 cm rainfall can remove 33 to 88% of imazaquin from the foliage, depending on the weed species and adjuvant. Imazaquin washed off from foliage in addition to any imazaquin not intercepted by foliage is then available for runoff or leaching. Of the total imazaquin available, at most 23% can move in runoff, depending upon ground coverage by crop and weeds. Information from the present studies provides a useful starting point for understanding the extent of foliar and runoff losses of imazaquin.

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Mention of trademarks or products does not constitute an endorsement of the products by the US Department of Agriculture and does not imply their approval to the exclusion of other products that may also be suitable.

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