Degradation and Disposal of Scepter Herbicide by Hydrogen Peroxide-Catalyzed Ozonation

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Studies were conducted to determine the ability of ozonation catalyzed by hydrogen peroxide (H_2O_2) to degrade solutions of Scepter herbicide (imazaquin). Scepter herbicide solutions were rapidly degraded using a range of solution temperatures (1−35 °C) and H_2O_2 concentrations (0−69 mM). The most rapid degradation occurred when the [H_2O_2] was 0.2 mM; imazaquin was also rapidly degraded in the absence of H_2O_2. The ozonation times required for 90% removal of the herbicide were typically < 15 min. Approximately 10.5 ± 4.4% (quinoline ring) to 17.1 ± 7.8% (carboxylic acid) of [^{14}C]imazaquin was oxidized to $^{14}CO_2$ when solutions with pH values ranging from 5.5 to 8.5 were ozonated for 0.5 h at 20 °C. Resulting ozonation products, which included nitrate, exhibited rapid biomineralization when added to two soils. The ozonation products of Scepter herbicide were not phytotoxic when applied to cotton, corn, and soybean seedlings at application rates equivalent to 34 g a.i./ha.

Keywords: *Imazaquin; ozonation; pesticide rinsate disposal; soil biomineralization*

INTRODUCTION

Ground water and soil contamination by pesticides has occurred at sites where pesticides were improperly handled, stored, and/or disposed (Habecker, 1989; Long, 1988)). In a study involving 1430 wells in 89 U.S. counties, wells located within 0.8 km of pesticide dealerships, formulators, or commercial applicators were more frequently contaminated by herbicides than wells located in other agricultural areas (Holden et al., 1992). In response to this contamination, concrete rinse pads are increasingly being used to collect equipment rinsate, spilled product, and tank overflows that occur at pesticide mixing−loading sites. Once collected, however, the problem remains of how to safely and effectively dispose of these pesticide-containing materials.

A variety of physical and chemical methods for degrading and/or detoxifying pesticide rinsate has been investigated. These include sorption onto activated carbon (Kobylinski et al., 1984) or peat moss (Berry et al., 1993) and treatment with acid or base (Honeycutt et al., 1988) or enzymes (Munnecke, 1980). Another approach to waste treatment and environmental remediation is the advanced oxidation processes (AOP), chemical oxidation techniques that generate highly oxidizing free radicals (Peyton, 1990).

One such AOP involves the catalytic decomposition of ozone (O_3) by hydrogen peroxide (actually the peroxide ion, HO_2^-) to hydroxyl ($HO^\bullet$) according to the following reaction (Staehelin and Hoigne, 1982):

$$H_2O_2 \leftrightarrow HO_2^- + H^+ \ (pK_a = 11.6) \qquad (1)$$

$$O_3 + HO_2^- \rightarrow HO^\bullet + O_2^- + O_2 \ (k = 2.8 \pm 10^6\ M^{-1}\ s^{-1}) \qquad (2)$$

Two potential advantages of this process are that reactions between $HO^\bullet$ and many pesticides in aqueous solution are rapid, some occurring at nearly diffusion-controlled rates (Haag and Yao, 1990), and that the ozonation products of some recalcitrant compounds exhibit enhanced biodegradability (Glaze, 1987; Somich et al., 1990; Leeson et al., 1993). Exploiting the latter advantage, a two-staged disposal system has been proposed (Somich et al., 1990) in which ozonation is coupled with a secondary microbial treatment for the more complete destruction of pesticide rinsate. Using a pilot-scale system, the major ozonation products of Aatrex herbicide (atrazine) were mineralized after approximately 30 h incubation with *Klebsiella terragena*, even in the presence of 36 mM NH_4NO_3 (Hapeman et al., 1995). Ammonium nitrate is a common fertilizer that can be present in equipment rinsate.

Imazaquin [2-(4-isopropyl-4-methyl-5-oxo-2-imidazolin-2-yl)-3-quinolinecarboxylic acid], an herbicide used to control broadleaf and grass weeds in soybean production, has a molecular weight of 311.3 g/mol, water solubility of 60 mg/L (distilled water at 25 °C), and vapor pressure < 2×10^{-8} mmHg at 45 °C (Ahrens, 1994). The susceptibility of imazaquin (Figure 1), or any member of the imidazolinone class of compounds, to ozonation has not been reported. Our objectives were to (1) determine the susceptibility of Scepter herbicide 1.5 AS (imazaquin) to ozonation, (2) determine the effect of hydrogen peroxide concentration, temperature, and solution pH on the ozonation process, and 3) assess the soil biodegradability and phytotoxicity of resulting ozonation products.

MATERIALS AND METHODS

Apparatus. Batch ozonation studies were conducted using a 200 cm × 2.5 cm glass reaction column. Ozone gas was generated by an OREC model V5-O ozonator (Ozone Research & Equipment Corp., Phoenix, AZ) using a 1 L/min dry oxygen feed and sparged into the bottom of the column via a glass diffuser. A 3.6 ± 0.1 g O_3/h output of the ozone unit was determined by reacting the ozone with 2% KI and titrating the liberated iodine with 0.10 N $Na_2S_2O_3$ in the presence of a starch indicator (American Public Health Association, 1989). Water was circulated through a water jacket surrounding the reaction column to control the temperature of the system. With the exception of a few fittings, all materials contacted by the ozone and herbicide solutions were made of glass or Teflon.

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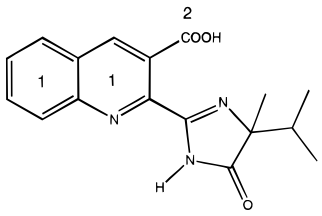
Imazaquin



(1) denotes quinoline ring (U) label position
(2) denotes carboxylic acid label position

3-Quinolinecarboxylic acid

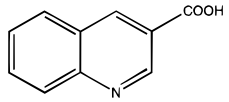


Figure 1. Molecular structures of imazaquin and 3-quinolinecarboxylic acid.

For studies involving [^{14}C]imazaquin, the off-gases were passed sequentially through two 100 mL gas traps, each containing 1 N KOH. The first gas trap typically removed >98% of the $^{14}CO_2$ trapped. The average total recovery of applied radioactivity from the ozonation system was 100 ± 6% (n = 6) (data not shown).

Reagents. Technical, analytical, and [^{14}C]imazaquin were gifts from the American Cyanamid Co., Princeton, NJ. The quinoline ring(U)-[^{14}C]imazaquin had a radiochemical purity of >97% and specific activity of 1.406 MBq/mg, and the carboxylic acid-[^{14}C]imazaquin had a radiochemical purity of >99% and specific activity of 0.7992 MBq/mg. The locations of the two radiolabel positions are shown in Figure 1. Solvents used were HPLC grade; other chemicals were reagent grade or purer and were obtained from Fisher Scientific. Stabilizers present in the 30% hydrogen peroxide (H_2O_2) solution were not removed prior to use.

Analytical Conditions. *Imazaquin Analysis.* The concentration of imazaquin remaining in solution was determined by HPLC using an ISCO (Lincoln, NE) Model 2350 UV absorbance detector set at 254 nm. A 12.5 cm × 0.46 cm C_{18} Whatman Partisphere column and isocratic mobile phase consisting of 30:69:1 acetonitrile:deionized water:acetic acid were used. The flow rate was 1.5 mL/min, and sample injection volume was 50 μL. Samples were stored at 4 °C and analyzed within 24 h after collection. The limit of quantitation for imazaquin was 0.05 mg/L.

Radioactivity Measurements. Radioactivity measurements of the herbicide solution and caustic traps were made by placing a 1 mL sample into 10 mL of ScintiVerse BD cocktail (Fisher Scientific) and counting for 10 min or 10 000 DPM with a Packard Instruments (Downers Grove, IL) Tri-Carb Model 4530 liquid scintillation counter. Corrections for background and quench were made automatically.

The presence of $^{14}CO_2$ in the 1 N KOH traps was confirmed qualitatively by combining 2 mL of KOH trapping solution with 1 mL of saturated $BaCl_2$ solution, centrifuging, and measuring the supernatant for radioactivity. Greater than 99% of the radioactivity present in the KOH trapping solution was absent in the supernatant, indicating the radioactivity was due to the formation of $^{14}CO_2$.

Nitrate Analysis. Analyses for nitrate (NO_3^-) were made according to EPA method 300.0 using a Dionex Model DX-300 ion chromatograph (Dionex Corp., Sunnyvale, CA). The limit of quantitation for NO_3^- was 0.01 mg/L. A control solution that consisted of reagent-grade deionized water was reacted with ozone for 1 h and showed no increase in nitrate concentration over time.

Effect of Scepter Herbicide Concentration. Solutions of Scepter herbicide were prepared at 57−893 mg/L imazaquin using reagent-grade water (ModuPure, Continental Water Systems, San Antonio, TX) in 0.020 M phosphate buffer (pH 7.0). These solutions were reacted with ozone at 20 ± 1 °C for 1 h; no H_2O_2 was added.

Effect of Solution Temperature and H_2O_2 Concentration. Solutions of Scepter herbicide containing 180 ± 7 mg/L imazaquin were prepared in 0.013 M borate (pH 8.5) and hydrogen peroxide added (0−69 mM). A solution pH of 8.5 was chosen to enhance the formation of peroxide ion (HO_2^-) from the added hydrogen peroxide (eq 1), thereby enhancing the catalytic degradation of aqueous ozone (eq 2). The solutions were covered to prevent photolysis, mixed thoroughly, and ozonated individually in the reaction column. Throughout the 0.5 h ozonation period, the temperature of the reaction was maintained at 1, 20, or 35 ± 1 °C, as appropriate. A 5 mL sample was collected via a sample port at regular time intervals; further reaction with ozone was prevented by addition of several Na_2SO_3 crystals (Adams and Randtke, 1992). Prior to sample collection, the port was flushed to ensure that fresh sample was collected. Preliminary studies indicated that imazaquin was stable at 35 °C in the presence of 69 mM H_2O_2 and was not stripped from solution by 1 L/min O_2 at 35 °C.

Effect of pH and ^{14}C-Label Position on Imazaquin Mineralization during Ozonation. Scepter herbicide solutions containing 230 ± 14 mg/L imazaquin were fortified with approximately 19.6 MBq of either quinoline-[^{14}C](U)-imazaquin or carboxylic acid-[^{14}C]imazaquin and prepared in either 0.013 M borate buffer (pH 8.5) or 0.020 M phosphate buffer (pH 7.0 and 5.5). These 500 mL solutions were reacted with O_3 for 0.5 h at 20 °C. After the last sampling, 40 mL of 1.8 N H_2SO_4 solution was added to acidify the solutions to pH ≤ 2. $^{14}CO_2$ produced by the mineralization of imazaquin during ozonation was collected in caustic traps.

Soil Bioassays of Ozonated Scepter Herbicide Solutions. *Effect of Ozonation, ^{14}C-Label Position, and Soil Series on Biomineralization.* Scepter herbicide solutions containing 180 ± 7 mg/L imazaquin were prepared using reagent-grade water in 0.0125 M borate buffer (pH 8.5). To two 600-mL Scepter solutions was added 6660 Bq (0.18 μCi) of either quinoline ring(U)-^{14}C-imazaquin or carboxylic acid−[^{14}C]-imazaquin. These solutions were ozonated separately for 1 h and measured for final radioactivity by LSC. No imazaquin was detected in the solutions after 0.5 h ozonation. Unozonated control solutions consisting of Scepter solution, plus either ring or carboxyl-labeled imazaquin, were also prepared. Ten milliliters of the ozonated or unozonated solutions were applied separately to 45 g (oven-dry equivalent) of moist Roxana sandy loam (pH 5.9, 0.8% OM; coarse-silty, mixed, nonacid, thermic, Typic Udifluvents) or Dardanelle silt loam (pH 6.2, 1.3% OM; fine-silty, mixed, thermic, Typic, Agriudolls) soils held in 500 mL biometer flasks. The flasks were vented regularly to maintain aerobic growth conditions. This study used a three-factor factorial arrangement of the treatments and three replications per treatment.

Effect of Solution pH and Ozonation Duration on Biomineralization. Scepter herbicide solutions containing 250 mg/L of imazaquin were prepared in either 0.013 M borate buffer (pH 8.5 + 13 mM H_2O_2) or 0.020 M phosphate buffer (pH 5.5, no H_2O_2). To these 500-mL solutions was added 9.25 MBq of quinoline(U)-[^{14}C]imazaquin. The solutions were ozonated for either 0.5 or 1 h, after which time any residual ozone remaining in solution was removed by addition of several Na_2SO_3 crystals. Nine milliliters of the ozonated Scepter solutions were applied to 45 g (oven-dry equivalent) of Roxana sandy loam or Dardanelle silt loam soils held in 500 mL biometer flasks. The moist soils were incubated for 19 d at 30 ± 1 °C. Control soils were treated with the appropriate unozonated Scepter herbicide solution, while blank soils were treated with pH-buffered water containing only several Na_2SO_3 crystals (no herbicide).

Plant Bioassays of Ozonated Scepter Herbicide Solutions. Studies were conducted to assess the phytotoxicity of ozonated Scepter herbicide solutions to three crop species. Four 500 mL solutions of Scepter herbicide solution containing 180 mg/L of imazaquin were prepared using natural well water (pH 7.2) collected in Crawford Co., AR. The solutions were ozonated separately for 2 h at 20 ± 1 °C and applied by spray chamber at 187 L/ha to flats containing either three to four leaf corn (*Zea mays* L.) Pioneer Hybrid 3245, two to three leaf cotton (*Gossypium hirsutum* L.) Delta Pine Originator, or V2-stage soybean (*Glycine max* (L.) Merr.) Pioneer 9442 seedlings. An unozonated herbicide solution (equivalent to 34 g of

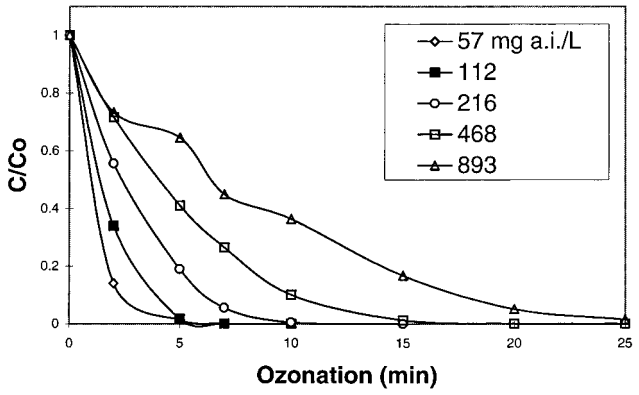


Figure 2. Removal of Scepter herbicide by ozonation at pH 7 and 20 °C.

imazaquin/ha) and a water-control solution (no herbicide) were applied for comparison. The heights of the plants were measured to the nearest millimeter at 7 days after treatment.

Statistical Analysis. For the effect of solution temperature and hydrogen peroxide study, the imazaquin concentrations were tabulated as proportions by dividing the concentration of imazaquin remaining at each sampling interval by the initial concentration and statistically analyzed using Proc ANOVA (SAS Institute, 1989). An *arc sine* transformation of these data did not affect the significance of any of the interactions tested, indicating that the variances were normally distributed (Gomez and Gomez, 1984). If appropriate after ANOVA, means were separated by the least significant difference test (SAS Institute, 1989). After the statistical analyses were performed, the data were multiplied by 100 and presented as percentages of the initial imazaquin concentrations that remained in solution at various stages of ozonation. Similar statistical analyses were performed for the mineralization and soil and plant bioassay studies, when appropriate.

RESULTS AND DISCUSSION

Effect of Scepter Herbicide Concentration. As shown in Figure 2, imazaquin concentrations ranging from 56 to 893 mg/L were readily degraded in deionized water (pH 7) at 20 °C. The high Scepter herbicide concentration was approximately 20% greater than would be present in a full-rate spray solution, assuming an application volume of 187 L/ha. Except for solutions with this high concentration, no imazaquin was detected in solution after 0.5 h ozonation. These data suggest that Scepter herbicide is susceptible to degradation by ozonation in the absence of hydrogen peroxide catalyst, even at concentrations higher than would be expected under actual-use conditions.

Effect of Temperature and H_2O_2 Concentration. A significant ($p = 0.0006$) temperature by [H_2O_2] by ozonation duration interaction was observed, indicating that the effect of H_2O_2 varied at different solution temperatures and at different periods of ozonation. The fastest degradation of Scepter herbicide occurred when 0.050−0.20 mM peroxide was added to solutions ozonated at 0−20 °C (Table 1). The addition of ≥3.2 mM H_2O_2 significantly reduced the rate of imazaquin degradation, presumably due to competition between imazaquin and excess H_2O_2 for O_3 and/or $HO^{\bullet}$ (Hoigne and Bader, 1976; Brunet et al., 1984). Similarly, Lacheur and Glaze (1996) found that the optimal removal of lysine required 0.15 mM H_2O_2. Some molecules may require higher H_2O_2 concentrations, as was seen by Masten et al. (1995), who found that the optimal removal of various chlorinated benzenes from water required 60 mM H_2O_2.

Table 1. Percentage of Initial Imazaquin (as Scepter Herbicide) Remaining in 0.013 M Borate Solution (pH 8.5) As Affected by Ozonation Duration, Hydrogen Peroxide Concentration, and Solution Temperature[a]

ozonation (min)	solution temp (°C)	hydrogen peroxide concentration (mM)						
		0	0.05	0.2	3	13	32	69
		(% imazaquin remaining)						
5	1	37.69	28.29	29.24	49.29	58.83	64.27	67.53
10	1	10.11	5.74	5.95	15.19	18.37	32.74	42.37
15	1	6.20	0.82	0.79	1.95	2.77	7.91	19.44
20	1	0.03	0.05	0.05	0.08	0.15	0.68	5.63
5	20	47.34	32.42	35.64	48.03	54.73	63.06	59.39
10	20	12.04	6.77	8.98	15.88	20.92	31.97	33.13
15	20	2.01	0.48	0.91	1.70	4.44	11.04	15.67
20	20	0.07	0.03	0.04	0.03	0.38	0.64	1.97
5	35	45.84	33.84	32.55	49.19	53.48	53.02	51.15
10	35	13.02	7.29	6.58	12.97	17.13	21.80	21.94
15	35	2.25	0.65	0.43	8.93	2.76	5.93	7.10
20	35	0.08	0.02	0.02	0.04	0.07	0.19	1.12

[a] These data were statistically analyzed as a split−split plot design using three replications, with the main plot factor as temperature, the subplot factor as hydrogen peroxide concentration, and sampling time as the sub-subplot factor. For comparisons between a set temperature and hydrogen peroxide concentration, LSD(0.05) = 4.2%. For comparisons within a set temperature, LSD(0.05) = 2.8%. For comparisons between any temperature or hydrogen peroxide concentration, LSD(0.05) = 3.4%.

Table 2. Mineralization of Imazaquin (as Scepter 1.5 AS Herbicide) during Ozonation as a Function of ^{14}C-Label Position and Solution pH[a]

^{14}C-label position	solution pH	mineralization (%)
COOH	5.5	8.4 a
COOH	7.0	23.6 b
COOH	8.5	19.4 bc
quinoline ring	5.5	10.7 a
quinoline ring	7.0	14.8 c
quinoline ring	8.5	6.1 a

[a] These data were statistically analyzed as a split−split plot with pH as the main plot, label position as the subplot, and time of sampling as the sub-subplot using three replications per treatment. Means followed by the same letter are not significantly different ($\alpha = 0.05$).

The degradation of imazaquin at 35 °C was slightly less affected by [H_2O_2] > 3.2 mM than either the 0 or 20 °C treatments (Table 1). The effects of hydrogen peroxide concentration and solution temperature were observed only during the first 20 min ozonation, however, and imazaquin was no longer detected in solution after 25 min ozonation, regardless of which temperature−[H_2O_2] combination was applied. For most combinations, the time for 90% removal of imazaquin from solution was less than 15 min. These data confirm the susceptibility of Scepter herbicide to ozonation and also show that the ozonation process effectively degrades the herbicide over a range of solution temperatures (1−35 °C) and hydrogen peroxide concentrations (0−69 mM).

Effect of pH on Mineralization of [^{14}C]Imazaquin during Ozonation. $^{14}CO_2$ was evolved during ozonation of radiolabeled imazaquin at all solution pH values investigated (pH 5.5, 7.0, 8.5). The percentages of imazaquin mineralized ranged from 6.1 ± 2.9% (quinoline ring at pH 8.5) to 23.6 ± 4.7% (COOH at pH 7.0). There was a significant ($p = 0.0011$) ^{14}C-label position by solution pH interaction. As might be expected, the greatest mineralization generally occurred from the COOH-labeled imazaquin (Table 2). Significantly more mineralization of the COOH-labeled imazaquin occurred at pH 8.5 than for the ring-labeled imazaquin. For both ^{14}C-label positions, the greatest

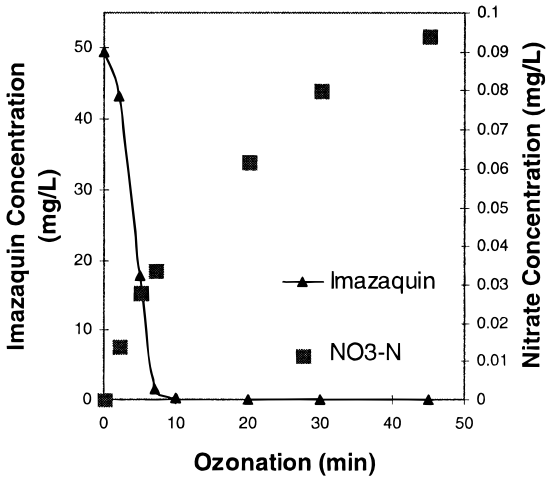


Figure 3. Production of NO_3^- during the ozonation of technical-grade imazaquin.

mineralization occurred when the solutions were maintained at pH 7.

Further evidence of imazaquin mineralization was obtained when ozonated solutions of technical-grade imazaquin (96.8% purity) were analyzed for nitrate (NO_3^-). NO_3^- was detected within two minutes of ozonation of technical-grade imazaquin (Figure 3) and also detected in ozonated solutions of 3-quinolinecarboxylic acid (3-QCOOH). 3-Quinolinecarboxylic acid (Figure 1) is an aqueous photolysis product of imazaquin (Mangels, 1991) and was thought to be a potential ozonation product of imazaquin resulting from the cleavage of imidazolinone and quinoline rings. The time required for 90% removal of 3-QCOOH at pH 6 and 22 °C was less than 5 min; this likely explains why 3-QCOOH was never observed in significant concentrations in ozonated solutions analyzed by HPLC.

The mineralization that occurred at the quinoline ring and carboxylic acid sites of imazaquin, and the detection of nitrate in solution, indicated that extensive degradation of the imazaquin molecule occurred during ozonation. In contrast, ozonation of the herbicide atrazine results primarily in the removal of *N*-alkyl groups since the oxidation and subsequent cleavage of the triazine ring does not readily occur (Adams and Randtke, 1992; Hapeman et al., 1995).

Biomineralization of Ozonated Scepter Herbicide Solutions. *Effect of Ozonation, ^{14}C-Label Position, and Soil Series on Biomineralization.* As has been observed for other herbicides (Kearney et al., 1988; Somich et al., 1990), ozonation resulted in reaction products that were rapidly mineralized by soil microorganisms. After 67 d incubation at 30 ± 1 °C, the soils receiving the ozonated Scepter herbicide solutions evolved an average of 56.3 ± 3.1% of the initially added ^{14}C as $^{14}CO_2$, as compared to only 2.7 ± 0.7% for those receiving the unozonated Scepter. These results indicated that the ozonation products of Scepter were readily degraded by soil microorganisms.

There was no significant ($p = 0.3702$) effect of ^{14}C-label position on soil biodegradation. This was likely due to the structure of imazaquin being extensively degraded during ozonation, as evidenced by the production of nitrate and $^{14}CO_2$ during ozonation. Thus, the soil microorganisms were likely presented with small fragments of the imazaquin molecule that contained little quinoline ring structure to impede utilization of the products as a source of carbon and/or energy. Nitrogen-containing ozonation products might also have been used as a nitrogen source (Leeson et al., 1993). In

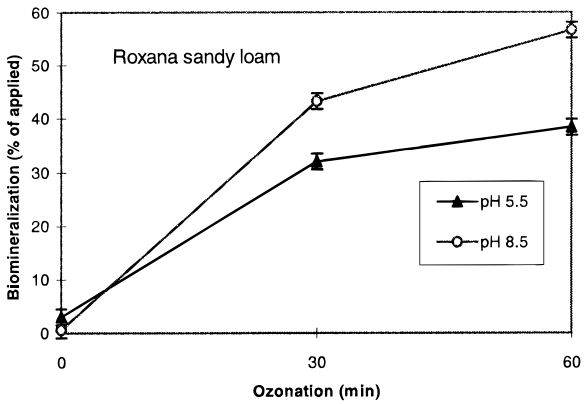


Figure 4. Biomineralization of ozonated Scepter solutions after 19 d incubation at 30 °C as a function of solution pH and duration of ozonation. (Standard error bars shown.)

terms of the soils treated with ozonated solutions, Dardanelle soils evolved the most $^{14}CO_2$ (62.2% of applied) as compared to 50.5% for Roxana soils (LSD-(0.05) = 5.6%).

Effect of Solution pH and Ozonation Duration on Biomineralization. There was a significant ($p < 0.0001$) soil by ozonation duration by solution pH interaction, indicating that the biomineralization of imazaquin ozonation products by two different soils was affected differently by solution pH and length of ozonation. When ozonated Scepter herbicide was applied to the Roxana sandy loam soil, $^{14}CO_2$ evolution increased with increasing ozonation time and initial solution pH. For the Roxana soils, mineralization ranged from 31.9% (0.5 h ozonation, pH 5.5) to 56.6% (1 h ozonation, pH 8.5) after 19 d incubation at 30 °C (Figure 4). A similar trend was observed for the Dardanelle soils except that the 1 h, pH 8.5 treatment evolved only 22.7% of the initially applied ^{14}C as $^{14}CO_2$. This trend was observed throughout the study for all three replications of this particular treatment, and might be due to the formation of a product(s) that resisted microbial degradation or that was utilized by microflora present in the Dardanelle soil. While the reason for this result is not known, it suggests that the ozonation conditions needed for the maximum biomineralization of ozonated pesticide solutions can vary between soils and/or microflora populations.

Phytotoxicity Bioassays. Cotton is damaged by Scepter herbicide (Barnes et al., 1989) and served as a good indicator of residual imazaquin in the ozonated Scepter solutions. For cotton, corn, and soybean seedlings, there were no significant ($p = 0.5414$) differences in plant heights between the water control and ozonated Scepter solutions. In addition, there was no visual evidence of damage (e.g., no spotting or burning of foliage) attributable to the imazaquin ozonation products. As would be expected, application of unozonated Scepter solutions significantly reduced the heights of both corn ($p < 0.0001$) and cotton ($p = 0.0003$) (Table 3). These results indicated that the products resulting from the ozonation of Scepter herbicide were nonphytotoxic when applied to corn, cotton, and soybean seedlings at a rate equivalent to 34 g/ha imazaquin.

Our results were consistent with those of Somich et al. (1990), who found that ozonation also effectively eliminates the phytotoxicity of atrazine, cyanazine and metolachlor in rinsate to wheat and soybean seedlings. Studies involving the ozonation of bromacil (Acher et al., 1994) indicate, however, that some rinsates may still exhibit phytotoxicity after ozonation. Their results indicate the importance of conducting toxicity assess-

Table 3. Seedling Heights (mm) 7 Days after Treatment with Ozonated or Unozonated Scepter Herbicide Solutions[a,b]

	height (mm)		
seedling type	water control	with O_3	without O_3
soybean (V2)	214 a	214 a	207 a
cotton (2−3 leaf)	140 b	145 b	110 c
corn (3−4 leaf)	297 d	291 d	236 e

[a] Application volume was 187/ha, equivalent to an application rate of 34 g a.i./ha. [b] These data were analyzed as a randomized complete block design with four replications per treatment. Means followed by the same letter are not significantly different ($\alpha = 0.05$).

ments on products resulting from chemical treatments of pesticides and also suggest that no single chemical treatment may be able to effectively degrade all rinsates to nonphytotoxic levels.

Conclusions. Imazaquin, the active ingredient in Scepter herbicide, was rapidly and extensively degraded by ozonation under a range of herbicide and hydrogen peroxide concentrations, solution pH values, and solution temperatures. The products that resulted from the ozonation of Scepter herbicide exhibited rapid biomineralization by soil microorganisms and reduced phytotoxicity to susceptible crop species. The ozonation conditions (e.g., solution pH, ozonation duration) that result in optimal biomineralization could depend upon the type of soil or microflora to which the ozonation products are applied. Ozonation was an effective means of degrading equipment rinsate containing imazaquin formulated as Scepter herbicide 1.5 AS.

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