JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY

Article

pubs.acs.org/JAFC

Photodegradation of the Isoxazolidine Fungicide SYP-Z048 in Aqueous Solution: Kinetics and Photoproducts

Pengfei Liu,[†] Yanjun Xu,[‡] Jianqiang Li,[†] Junli Liu,[§] Yongsong Cao,[†] and Xili Liu*[,†]

[†]College of Agriculture and Biotechnology, and [‡]College of Science, China Agricultural University, Beijing 100193, People's Republic of China

[§]Shenyang Research Institute of Chemical Industry, Shenyang 110021, People's Republic of China

ABSTRACT: Previous research has demonstrated that 3-[5-(4-chlorophenyl)-2,3-dimethyl-3-isoxazolidinyl]pyridine (SYP-Z048), a newly developed nitrogen heterocycle substituted isoxazolidine compound, has good protective and curative activities against a wide range of fungal diseases of fruits and vegetables caused by Ascomycetes, Basidiomycetes, and Deuteromycetes. In this study, the photochemical behavior of SYP-Z048 was investigated in aqueous solution and in response to solar and low-pressure mercury ultraviolet (UV) lamp irradiation. SYP-Z048 photolysis was pH- and temperature-dependent and was described by a first-order degradation reaction. A total of 11 photoproducts were separated by high-performance liquid chromatography (HPLC) and solid-phase extraction (SPE) and were identified on the basis of ^{1}H and ^{13}C nuclear magnetic resonance (NMR) and high-performance liquid chromatography−mass spectrometry (HPLC−MS) spectra. The photoproduct structures and kinetics suggested that the phototransformation of SYP-Z048 occurred via multiple reaction pathways that included the cleavage of the N−O bond in the isoxazolidine ring and the dechlorination of the benzene ring.

KEYWORDS: *SYP-Z048, photodegradation kinetics, photodegradation pathway, photoproducts*

1. INTRODUCTION

Because chemical pesticides are effective and easy to apply, they have been widely used to increase crop yields. Once applied, however, the pesticides may suffer photodegradation, hydrolysis, or biodegradation,[1,2] and the degradation products may be stable and toxic to non-target organisms.[2,3] The widespread occurrence of pesticides and their degradation products in the environment and food commodities has concerned environmentalists and food chemists.[4,5]

3-[5-(4-Chlorophenyl)-2,3-dimethyl-3-isoxazolidinyl]-pyridine (SYP-Z048), an isoxazolidine class fungicide,[6] was developed by the Shenyang Research Institute of Chemical Industry for control of tomato gray mold. Isoxazolines are a relatively new class of chemicals and have substantial antimicrobial activities.[7] A series of agrochemicals with isoxazoline as the functional group have been designed, synthesized, and applied for crop protection.[8,9] As one analogue of these new chemicals, SYP-Z048 has protective and curative activities against a wide range of fungal diseases caused by Ascomycetes, Basidiomycetes, and Deuteromycetes in fruits and vegetables.[10,11] Like many other fungicides that inhibit demethylation ("DMI fungicides"), SYP-Z048 is an ergosterol synthesis inhibitor[12] and has low mammalian toxicity, with no genotoxicity or teratogenicity to rats.[13,14]

Pesticide photodegration products are an important type of organic pollutant.[15−17] Photolysis is a major process by which pesticides are transformed[18,19] and frequently occurs in the atmosphere and on the surface of water, soil, and plants.[20−23] The photoproducts generated by photolysis are in some cases more toxic and damaging to the environment than their parent compounds.[24,25] As a result, researchers are now identifying photoproducts and determining their toxicity as part of pesticide risk assessment.[26] Identification of photoproducts can be difficult,[27] however, because the structures can be complex, are often unknown, and can occur at very low concentrations in the environment. To determine the degradation pathway of a new pesticide, researchers must obtain sufficient photoproducts and use multiple analytic methods, including high-performance liquid chromatography−mass spectrometry (HPLC−MS), gas chromatography−mass spectrometry (GC−MS), and nuclear magnetic resonance (NMR).

Although reactions resulting in the "ring-opening" of the heterocycle moiety during isoxazoline and isoxazolidine photodegradation have been described,[28,29] the fate of SYP-Z048 in the environment has not been investigated in depth. The goal of the current study is to elucidate the photochemical behavior of SYP-Z048 in aqueous solution. SYP-Z048 photolysis kinetics are evaluated; a large number of photoproducts are identified; and a detailed degradation pathway is proposed.

2. MATERIALS AND METHODS

2.1. Chemicals and Reagents. SYP-Z048 (99.3% purity) was obtained from the Shenyang Research Institute of Chemical Industry. The standards, 2-methylpyridine (98.0% purity), 3-methylpyridine (99.5% purity), 1-chloro-4-methylbenzene (98.0% purity), 4-chlorobenzaldehyde (97.0% purity), and 1-(4-chlorophenyl)ethanone (97.0% purity), were purchased from Sigma-Aldrich. HPLC-grade methanol was purchased from Fisher Scientific. Ultrapure water was obtained with a Millipore water purification system (Milli-Q, Bedford, MA). SYP-Z048 and photoproduct standard solutions and SYP-Z048 working solutions were prepared by dissolving SYP-Z048 in water/

Received: August 9, 2012
Revised: October 31, 2012
Accepted: November 6, 2012
Published: November 6, 2012

dx.doi.org/10.1021/jf3034607 | J. Agric. Food Chem. 2012, 60, 11657−11663

methanol (99:1, v/v). All other reagents were analytical-grade and used as received.

2.2. Photodegradation Experiments. The photodegradation reactions were performed in a quartz tube. The aqueous solution was irradiated through the wall of the quartz tube using a low-pressure mercury lamp (250 W, λ = 254 nm) or direct sunlight. The light intensity of the mercury lamp at 254 nm was 700 μW cm^{-2}, as measured with a ZDZ-1 ultraviolet (UV) irradiation photometer. The solar irradiation experiments were performed during the summer (from June to August, 2009) at the China Agricultural University, Beijing, China (40° 27′ 53.73″ N, 116° 27′ 36.96″ E).

To investigate the kinetics of SYP-Z048 or its main photoproducts, 20 mL aliquots of 10.0 μg mL^{-1} SYP-Z048 in water/methanol (99:1, v/v) were irradiated under a low-pressure mercury lamp or sunlight. Samples from the solution were taken at regular intervals for HPLC–MS analysis. The effect of pH was determined with solutions that were buffered by 40 mM KH_2PO_4 and adjusted to pH 5, 7, and 9 by the addition of NaOH. The effect of the temperature (30 and 50 °C) under UV irradiation was also evaluated.

To acquire large amounts of photoproducts, 100.0 μg mL^{-1} SYP-Z048 in non-buffered water/methanol (99:1, v/v) was irradiated for 45 min under a low-pressure mercury lamp at 50 °C. The irradiated solution was collected for direct HPLC–MS or NMR analysis after a further separation. Some main photoproducts were further confirmed by analyzing standards on HPLC.

2.3. HPLC–MS Analysis. SYP-Z048 and photoproducts irritated by an UV lamp and sunlight were analyzed by the Agilent 1100 HPLC–mass selective detector (MSD) system with an atmospheric pressure electrospray ionization (API–ES) ion source and a diode array detector (Agilent Technologies) equipped with a pre-column and a VP-ODS (5 μm, 250 × 4.6 mm) column. The mobile phase consisted of CH_3OH (A) and H_2O (B). The following conditions were used: 40% B from 0 to 4 min and then from 40 to 20% B in 12 min. The injection volume was 5 μL, and the flow rate was 1 mL min^{-1}. The MS detection was performed using API–ES in positive modes. A capillary potential of 100 V, a N_2 drying gas flow of 10 L min^{-1} at 320 °C, and a nebulizer pressure of 35 psi were maintained for analysis. The post-column split condition was 30% mobile phase to the MSD and 70% mobile phase to the waste bottle. The scan range was 80–800 atomic mass units (amu), and the capillary voltage was 4000 V.

2.4. Photoproduct Pretreatment and NMR Analysis. Because exposure of SYP-Z048 in aqueous solution to light generated a mixture of photoproducts at very low concentrations, pre-concentration and separation steps were required before NMR analysis. For pre-concentration, a collected sample of 1.5 L containing 100.0 μg mL^{-1} SYP-Z048 was extracted on a Visiprep solid-phase extraction (SPE) vacuum manifold. The samples of photoproducts were added to ENVI-18 SPE cartridges (SUPCO, 300 mg), which were pre-conditioned with methanol and ultrapure water. After the pre-concentrated analytes were held in the cartridges, the photoproducts were eluted from the cartridges using 3 mL of methanol. SYP-Z048 photoproducts were separated by HPLC using the conditions described in section 2.3. Each peak eluate was collected manually on the basis of visual inspection of the chromatogram. The same fractions were combined; the solvent was removed by passage through ENVI-18 SPE cartridges (SUPCO, 300 mg); and the fractions were then vacuumed to dryness in a desiccator. About 1 mg of each product was dissolved in deuterated methanol (CD_3OD) for NMR analysis (INOVA-50; tetermethylsilane was the internal standard).

2.5. Statistical Analysis. SYP-Z048 concentrations were fit to a first-order degradation equation $C_t = C_0\, e^{-kt}$, where C_t is the SYP-Z048 concentration at time t, C_0 is the initial concentration of SYP-Z048, k is the degradation rate, and t is the time. The half-life, $t_{1/2}$, was calculated from the equation $t_{1/2} = 0.693/k$.

3. RESULTS AND DISCUSSION

3.1. Photodegradation Kinetics. The UV–vis absorption spectrum of SYP-Z048 in aqueous solution showed absorbance from 200 to 350 nm with two characteristic bands at 212 and 223 nm and a shoulder at 261 nm (Figure 1). The absorption spectral range above 290 nm suggested that SYP-Z048 could degrade under solar light.

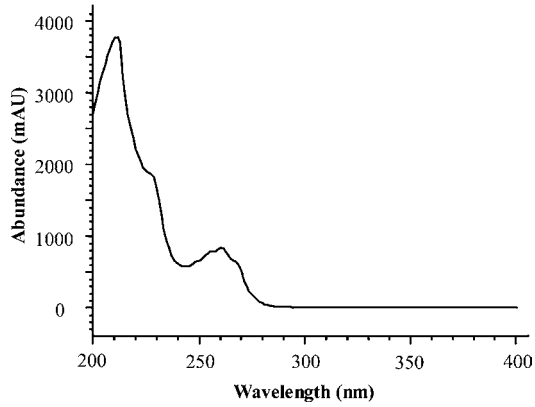


Figure 1. Absorption spectrum of SYP-Z048 in a water/methanol (99:1) solution.

SYP-Z048 photodegradation experiments were carried out under sunlight and UV light. To evaluate the effect of hydrolysis during the experiments, SYP-Z048 in buffer solution (pH 5, 7, and 9) was kept in darkness for 7 days at 30 and 50 °C. The results showed no obvious SYP-Z048 degradation (data not shown). Within 7 days of solar irradiation, photodegradation was 37, 76, and 75% in solutions buffered to pH 5, 7, and 9 (Figure 2a). Photolysis was much faster with UV irradiation than with solar radiation; with UV irradiation, more than 82% of the SYP-Z048 was degraded in 120 min at 30 °C (Figure 2b) and in 7 min at 50 °C (Figure 2c). With either sunlight or UV light, the SYP-Z048 concentration declined logarithmically with irradiation time, indicating a first-order degradation process.

An influence of solution pH on the pesticide photodegradation rate has been previously reported.[30−32] An effect of pH on the SYP-Z048 photodegradation rate was clearly demonstrated in the current study (Figure 2). With solar radiation, the photodegradation rate (k) was much greater at pH 7 and 9 than at pH 5 (Figure 2a); the half-life ($t_{1/2}$) with solar degradation was 11.2, 5.0, and 5.3 days at pH 5, 7, and 9, respectively. The effect of pH was smaller with UV irradiation than with solar irradiation, but SYP-Z048 degradation with UV radiation tended to be slower at pH 5 than at pH 7 and 9 (Figure 2b). Apparently, acidic conditions hindered degradation of SYP-Z048, and a similar observation has been reported on ciprofloxacin.[33]

When the temperature was increased from 30 to 50 °C, the half-life of SYP-Z048 under UV radiation decreased about 20 times (Figure 2b versus Figure 2c). This finding is consistent with many reports that the rate of pesticide degradation increases with the temperature.[34,35]

When a SYP-Z048 solution (with an initial concentration of 100 μg mL^{-1}) was irradiated by UV light for 45 min at 50 °C, 11 main photoproducts and 2 isomers of SYP-Z048 were detected by HPLC–MS (Figure 3). They were denoted with uppercase letters A–M based on elution sequence, in which K and L represent isomers of SYP-Z048, which are described later. Kinetics curves (Figure 4) for photoproducts A, B, C, E, F, G, I, and M were obtained from buffered solutions (pH 7)

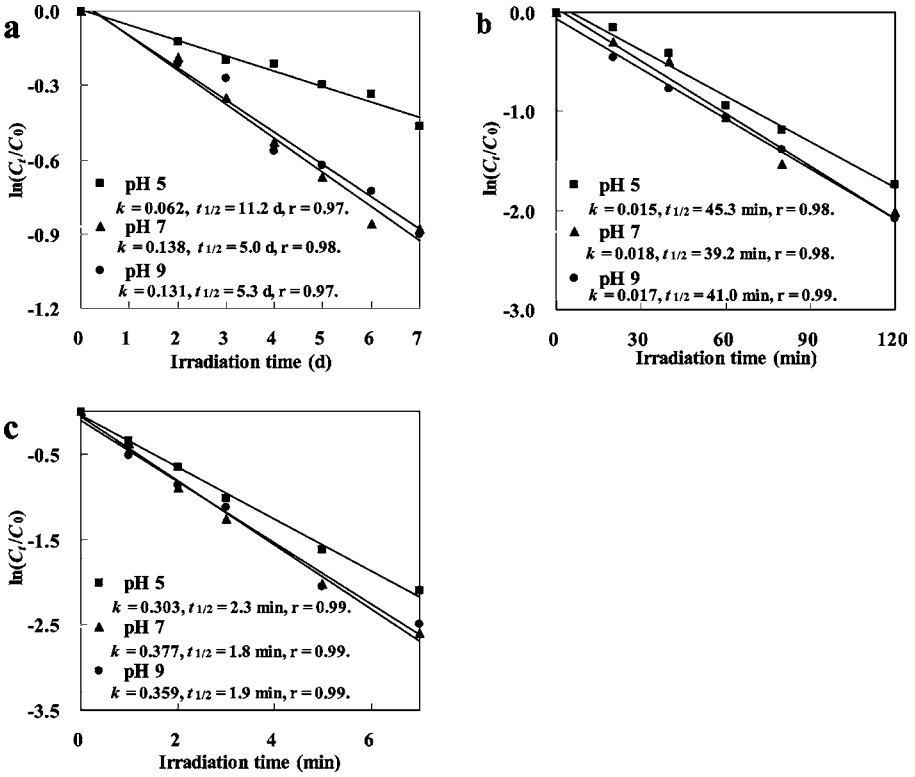


Figure 2. Kinetics of SYP-Z048 photodegradation in aqueous solutions (pH 5, 7, and 9) exposed to (a) solar irradiation at 30 °C, (b) UV irradiation at 30 °C, and (c) UV irradiation at 50 °C. The initial concentration of SYP-Z048 was 10 μg mL^{-1}. Lines represent linear regressions.

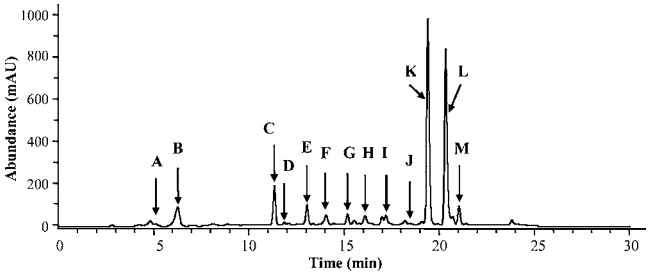


Figure 3. HPLC chromatogram of a SYP-Z048 solution after 45 min of high-pressure mercury lamp irradiation. Areas were determined at 254 nm.

during a 220 min exposure to irradiation using the low-pressure mercury UV lamp at 30 °C. Products D, H, and J were not detected under this reaction condition. More than 97% of SYP-Z048 was degraded after 220 min of irradiation, with the major degradation products as B and F (Figure 4a). Compounds A, I, and M accumulated quickly, early during irradiation, and then decreased after 20 or 80 min (Figure 4b), indicating that they might be primary products. The delayed appearance of compound G suggested that it could be a secondary product. The decline in the concentration of compound G after 120 min suggested that was further transformed into other products. During the irradiation period, compounds B, C, E, and F accumulated in the solution without any further degradation.

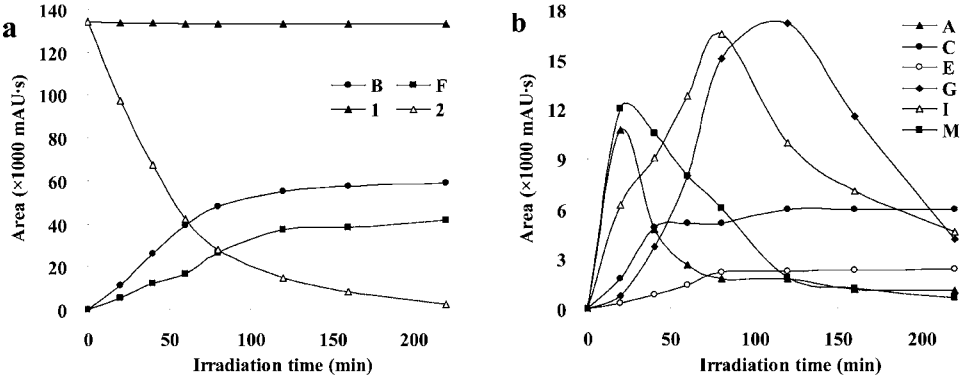
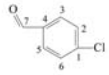
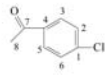
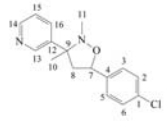
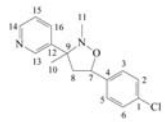
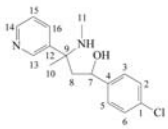


Figure 4. Degradation of SYP-Z048 in pH 7 solutions at 30 °C in the dark (1) and during UV irradiation (2) and the concentrations of principal photoproducts (indicated by uppercase letters) during the irradiation. A high-pressure mercury UV lamp was used. The initial concentration of SYP-Z048 was 10 μg mL^{-1}. Concentrations of SYP-Z048 and products B and F are shown in panel a. Concentrations of products A, C, E, G, I, and M are shown in panel b.

dx.doi.org/10.1021/jf3034607 | J. Agric. Food Chem. 2012, 60, 11657−11663

Table 1. ^{1}H and ^{13}C NMR Chemical Shifts (δ, ppm) and H,H-Coupling Constants ($^{3}J_{H,H}$, Hz) of Photoproducts B, C, E, F, G, M, and SYP-Z048 (K, *Z* Isomer; L, *E* Isomer)

Analytes	Structural formula	R_t (min)	^{1}H δ (ppm)	^{13}C δ (ppm)
B		6.3	H-6: 2.593 (s, 3H); H-4: 7.524 (m, 1H); H-2: 8.328 (m, 1H); H-3: 8.678 (d, *J*=3.5, 1H); H-5: 9.058 (s, 1H).	C-6: 27.122; C-4: 125.699; C-2: 134.416; C-3: 137.962; C-5: 150.595; C-1: 154.210.
C		11.3	H-7: 2.850 (s, 3H); H-3, 5: 7.405 (d, *J*=8.5, 2H); H-2, 6: 7.731 (d, *J*=8.5, 2H).	C-7: 27.221; C-2, 6: 130.032; C-3, 5: 130.18; C-1: 134.570; C-4: 138.947.
E		13.1	H-6: 2.126 (s, 3H); H-4: 7.362 (m, 1H); H-3: 7.891 (m, 1H); H-5: 8.369 (d, *J*=4, 1H); H-1: 8.594 (s, 1H).	C-6: 21.646; C-4: 115.318; C-2: 125.153; C-3: 135.167; C-5: 147.276; C-1: 148.910.
F		14.1	H-2, 6: 7.574 (d, *J*=8.5, 2H); H-3, 5: 7.866 (d, *J*=8.5, 2H); H-7: 9.912 (s, 1H).	C-2, 6: 130.819; C-3, 5: 132.409; C-4: 136.852; C-1: 142.126; C-7: 193.160.
G		15.1	H-8: 2.535 (s, 3H); H-2, 6: 7.491 (d, *J*=8.5, 2H); H-3, 5: 7.928 (d, *J*=8.5, 2H).	C-8: 26.961; C-2, 6: 130.251; C-3, 5: 131.413; C-4: 137.214; C-1: 140.925; C-7: 199.504.
K		19.4	H-10: 1.526 (s, 3H); H-8: 2.505-2.983 (m, 2H); H-11: 2.607 (s, 3H); H-7: 5.285 (dd, *J*=6, *J*=6.5 1H); H-3, 5: 7.038 (d, *J*=8, 2H); H-2, 6: 7.137 (d, *J*=6.5, 2H); H-15: 7.310 (dd, *J*=5, *J*=5, 1H); H-16: 7.908 (d, *J*=, 1H); H-14: 8.331 (d, *J*=5, 1H); H-13: 8.635 (s, 1H).	C-10: 22.836; C-11: 39.330; C-8: 52.219; C-9: 70.548; C-7: 79.401; C-15: 125.153; C-2, 6: 128.980; C-3, 5: 129.643; C-1: 134.295: C-16: 137.075; C-4: 142.602; C-12: 143.606; C-14: 148.595; C-13: 149.023.
L		20.3	H-10: 1.523 (s, 3H); H-8: 2.370-3.027 (m, 2H); H-11: 2.583 (s, 3H); H-7: 4.878 (m, 1H); H-3, 5: 7.292 (d, *J*=8, 2H); H-2, 6: 7.339 (d, *J*=8.5, 2H); H-15: 7.396 (dd, *J*=5, *J*=4.5, 1H); H-16: 8.331 (d, *J*=4.5, 1H); H-14: 8.399 (d, *J*=8, 1H); H-13: 8.746 (s, 1H).	C-10: 23.115; C-11: 40.480; C-8: 51.424; C-9: 70.086; C-7: 80.445; C-15: 125.153; C-2, 6: 129.186; C-3, 5: 130.193; C1: 134.661; C-16: 137.075; C-4: 141.800; C-12: 142.800; C-14: 148.833; C-13: 148.877.
M		21.2	H-10: 1.562 (s, 3H); NH: 1.977 (s, 1H); H-8: 2.464-2.913 (m, 2H); H-11: 2.537 (s, 3H); H-7: 3.740 (m, 1H); OH: 4.970 (br, 1H); H-3, 5: 7.106 (d, *J*=8.5, 2H); H-2, 6: 7.203 (d, *J*=8, 2H); H-15: 7.371 (dd, *J*=5, 5.5, 1H); H-16: 8.364 (d, *J*=4, 1H); H-14: 8.399 (d, *J*=8, 1H); H-13: 8.634 (s, 1H).	C-10: 30.213; C-11: 43.689; C-9: 55.069; C-8: 75.134; C-7: 82.221; C-15: 125.204; C-2, 6: 130.079; C-3, 5: 130.706; C-1: 135.013; C-16: 135.552; C-4: 139.064; C-12: 146.870; C-14: 147.569; C-13: 148.375.

3.2. Identification of the Photoproducts. Photoproducts B, C, E, F, G, and M were separated and identified by ^{1}H and ^{13}C NMR (Table 1), and A, D, H, I, and J were identified by HPLC–MS (Table 2).

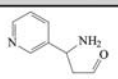
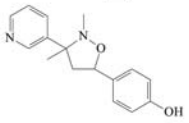
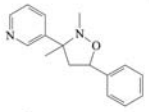
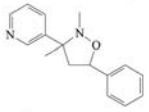
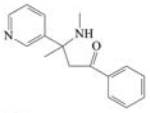
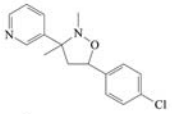
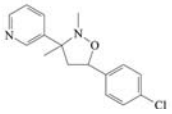
K and L were identified as isomers of SYP-Z048 because their retention times, molecular ion peaks, and fragmentation patterns were essentially the same as those of the SYP-Z048 standard. The peaks at *m*/*z* 310.9, 150.9, and 172.9 were temporarily identified as $(M + Na)^+$, ( + H)$^+$, and ( + Na)$^+$ ions. The NMR data were basically consistent with a previous report.[6]

According to the key resonances and their assignment presented in Table 1, the compounds B, C, E, F, and G were identified as 2-methylpyridine, 1-chloro-4-methylbenzene, 3-methylpyridine, 4-chlorobenzaldehyde, and 1-(4-chlorophenyl)ethanone, respectively. HPLC analyzing of the five compound standards also confirmed the results.

The ^{1}H and ^{13}C NMR spectra for compound M were similar to those of the parent compound; they differed only in some chemical shifts. Thus, compound M was identified as 1-(4-chlorophenyl)-3-(methylamino)-3-(pyridine-3-yl)butan-1-ol, which might be produced by the opening of the SYP-Z048 isoxazolidine ring induced by the cleavage of the N–O bond. The ring-opening reaction of heterocycles through cleavage of the labile N–O bond under UV irradiation was also reported by Mukai et al.[34] and Singh et al.[35] The compound M experienced a further degradation under UV irradiation and produced methyl pyridine (B and E) and derivatives of chlorobenzene (C, F, and G). This conjecture is in accordance with the kinetics of the compound.

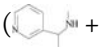
The molecular ion peak of D was 18 mass units lower than that of SYP-Z048, and the mass spectra of D lacked a chlorine isotope peak. A characteristic fragment ion of the parent compound was also evident at *m*/*z* 150.9. D, which might be produced by the dechlorination and hydroxylation of SYP-

Table 2. HPLC−MS Analysis of SYP-Z048 and Photoproducts after 45 min of Irradiation under the High-Pressure Mercury Lamp in Water/Methanol Solution (99:1)

Analytes	Substance	Structural formula	R_t (min)	Main fragments ions (m/z) amu ES+
A	3-amino-3-(pyridin-3-yl)propanal		5.1	150.9(M+H)$^+$; 172.9(M+Na)$^+$
D	4-(2,3-dimethyl-3-(pyridine-3-yl)isoxazolidin-5-yl)phenol		11.9	271.0(M+H)$^+$; 293.0(M+Na)$^+$; 150.9
H	2,3-dimethyl-5-phenyl-3-(pyridine-3-yl)		16.1	255(M+H)$^+$; 172.9; 150.9
I	2,3-dimethyl-5-phenyl-3-(pyridine-3-yl)		17.2	255(M+H)$^+$; 172.9; 150.9
J	3-(merhylamino)-1-phenyl-3-(pyridine-3-yl)butan-1-one		18.3	255(M+H)$^+$; 136; 120
K	3-[5-(4-chlorophenyl)-2,3-dimethyl-3-isoxazolidinyl]pyridine		19.4	289(M+H)$^+$; 291; 310.9(M+Na)$^+$; 172.9; 150.9
L	3-[5-(4-chlorophenyl)-2,3-dimethyl-3-isoxazolidinyl]pyridine		20.3	289(M+H)$^+$; 291; 310.9(M+Na)$^+$; 172.9; 150.9

Z048, was identified as 4-(2,3-dimethyl-3-(pyridine-3-yl)-isoxazolidin-5-yl)phenol.

For the compounds H and I, the molecular ions at m/z 255 were 35 mass units lower than those of SYP-Z048 and no chlorine isotope peaks were evident. They were identified as $(M - Cl + H)^+$. The fragmentation patterns of compounds H and I at m/z 150.9 and 172.9 were similar to those of SYP-Z048, suggesting that the main molecular skeleton had not changed. Consequently, compounds H and I were identified as isomers of 2,3-dimethyl-5-phenyl-3-(pyridine-3-yl)-isoxazolidine.

The fragment ions of compound J were quite different from those of compounds H and I, although the molecular ion was also at m/z 255. The fragments of compound J at m/z 136 and 120 are probably ( + H)$^+$ and ( + H)$^+$ ions. On the basis of mass information, compound J might result from a cleavage in the N−O bond of compounds H or I, which would induce the opening of the isoxazolidine ring and produce 3-(merhylamino)-1-phenyl-3-(pyridine-3-yl)butan-1-one.

Compound A had molecular ion peaks at m/z 150.9 (M + H)$^+$ and m/z 172.9 (M + Na)$^+$, indicating that it had the same fragment ions as the parent compound. Compound A was identified as 3-amino-3-(pyridin-3-yl)propanal and might be produced by demethylation and benzene ring reduction of compound J.

3.3. Proposed Degradation Pathway. On the basis of the degradation products and kinetics, two possible pathways for the photodegradation of SYP-Z048 in aqueous solution are proposed in Figure 5. The first pathway is initiated by the opening of the isoxazolidine ring at bond N−O to yield compound M. Then, 4-chlorobenzaldehyde, 1-(4-chlorophenyl)ethanone, 2-methylpyridine, and 3-methylpyridine are formed by the cleaving of chlorinephenylaminopyridine, and they are subsequently converted into 1-chloro-4-methylbenzene by the demethyl reaction. The second pathway is initiated by the dechlorination of the benzene ring at chlorine; subsequent oxidation produces compounds D, H, and I. Compounds D, H, and I are further degraded into compounds J and A by the opening of the isoxazolidine ring. Compounds J and A are finally transformed into 2-methylpyridine and 3-methylpyridine.

3.4. Photolysis of SYP-Z048 under Different Light Sources. UV irradiation generated more photoproducts than solar radiation. The main products of the two proposed pathways were similar with both solar and UV radiation, except that the following compounds were not produced with solar radiation: 3-amino-3-(pyridin-3-yl)propanal (A), 2-methylpyridine (C), 4-(2,3-dimethyl-3-(pyridine-3-yl)isoxazolidin-5-yl)-phenol (D), and 2,3-dimethyl-5-phenyl-3-(pyridine-3-yl) (H). Overall, these results suggest that the proposed photolysis pathways may occur in the natural environment.

3.5. Toxicity of SYP-Z048 Photoproducts. The acute aquatic toxicity criterion was described by The Globally Harmonized System of Classification and Labeling of Chemicals (GHS). According to the acute toxicity data (which were generated with fish) from the Sigma-Aldrich Safety Data Sheet,[36] the SYP-Z048 photoproducts identified here have different potentials for harming aquatic organisms. The compound 4-chlorobenzaldehyde (F) is assigned to GHS Acute Category II; 2-methylpyridine (B) and 1-(4-chlorophenyl)ethanone (G) are assigned to GHS Acute

dx.doi.org/10.1021/jf3034607 | J. Agric. Food Chem. 2012, 60, 11657−11663

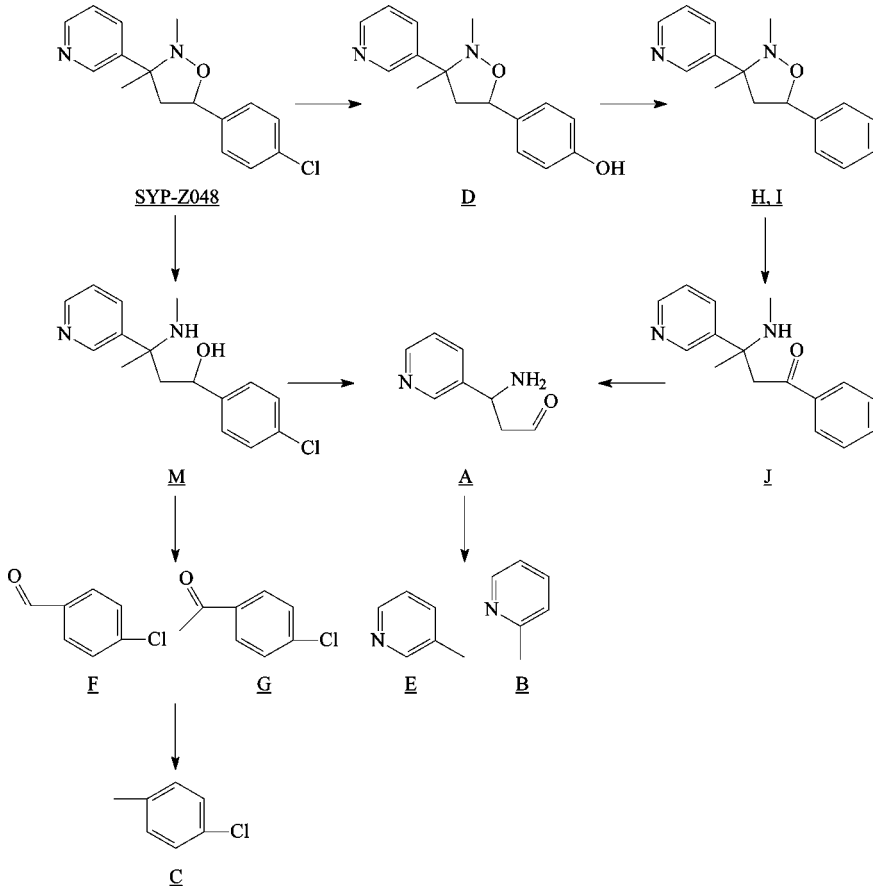


Figure 5. Presumed pathways for SYP-Z048 photodegradation by UV irradiation.

Category III; and 3-methylpyridine (E) has no acute aquatic toxicity. However, the toxicities of the other products of SYP-Z048 photolysis are unclear. Additional research is needed regarding the toxicity of SYP-Z048 photoproducts to non-target organisms in the natural environment.

AUTHOR INFORMATION

Corresponding Author

*Telephone/Fax: +86-10-62731013. E-mail: seedling@cau.edu.cn.

Funding

We gratefully acknowledge the National Natural Science Foundation of China (31000866) for financial support.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We are grateful to Jibo Lin, Mingan Wang, and Yanhong Dong for advice and assistance in the HPLC–MS and NMR analyses. We also thank the Chinese Academy of Medical Sciences for their NMR analysis.

REFERENCES

(1) Tixier, C.; Sancelme, M.; Aït-Aïssa, S.; Widehem, P.; Bonnemoy, F.; Cuer, A.; Truffaut, N.; Veschambre, H. Biotransformation of phenylurea herbicides by a soil bacterial strain, *Arthrobacter* sp. N2: Structure, ecotoxicity and fate of diuron metabolite with soil fungi. *Chemosphere* **2002**, *46* (4), 519–526.

(2) Gupta, B.; Rani, M.; Kumar, R.; Dureja, P. Decay profile and metabolic pathways of quinalphos in water, soil and plants. *Chemosphere* **2011**, *85* (5), 710–716.

(3) Boudina, A.; Emmelin., C.; Baaliouamer, A.; Païssé, O.; Chovelon, J. M. Photochemical transformation of azoxystrobin in aqueous solutions. *Chemosphere* **2007**, *68* (7), 1280–1288.

(4) Yang, R. Q.; Lv, A. H.; Shi, J. B.; Jiang, G. B. The levels and distribution of organochlorine pesticides (OCPs) in sediments from the Haihe River, China. *Chemosphere* **2005**, *61* (3), 347–354.

(5) Allaoui, A.; Malouki, M. A.; Wong-Wah-Chung, P. Efficient degradation of methabenzthiazuron photoinduced by decatungstate anion in water: Kinetics and mechanistic studies. *Chemosphere* **2011**, *85* (4), 558–564.

(6) Shaber, S. H; Zhang, L. X.; Szapacs, E. M.; Quinn, J. A. Heterocyclic substituted isoxazolidines and their use as fungicides. U.S. Patent 6,313,147.B1, 2001.

(7) Milinkevich, K. A.; Yoo, C. L.; Sparks, T. C.; Lorsbach, B. A.; Kurth, M. J. Synthesis and biological activity of 2-(4,5-dihydroisoxazol-5-yl)-1,3,4-oxadiazoles. *Bioorg. Med. Chem. Lett.* **2009**, *19* (19), 5796–5798.

(8) Rajanarendar, E.; Nagi Reddy, M.; Rama Krishna, S.; Rama Murthy, K.; Reddy, Y. N.; Rajam, M. V. Design, synthesis, antimicrobial, anti-inflammatory and analgesic activity of novel isoxazolyl pyrimido[4,5-*b*]quinolines and isoxazolyl chromeno[2,3-*d*]pyrimidin-4-ones. *Eur. J. Med. Chem.* **2012**, *55*, 273–283.

(9) Weinig, H.-G.; Passacantilli, P.; Colapietro, M.; Piancatelli, G. Glycal-mediated synthesis of enantiomerically pure 5-substituted isoxazoles containing a differentially O-benzylated glycerol moiety. *Tetrahedron Lett.* **2002**, *43* (26), 4613–4615.

(10) Liu, J. L.; Si, N. G.; Chen, L.; Zhang, D. M.; Zhang, Z. J. Biological activity against tomato leaf mold and application of a novel fungicide, SYP-Z048(III). *Chin. J. Pestic.* **2004**, *43* (3), 103–105.

(11) Si, N. G.; Zhang, Z. J.; Liu, J. L.; Li, Z. N.; Zhang, D. M.; Chen, L.; Wang, L. Z. Biological activity and application of a novel fungicide: SYP-Z048(I). *Chin. J. Pestic.* **2004**, *43* (1), 16−18.
(12) Han, P.; Liu, X. L.; Liu, P. F.; Si, N. G. Effect of novel fungicide 5-(4-chloro pheny1)-2,3-dimethyl-3-(pyridine-3)-oxazoline on ergosterol biosynthesis in *Botrytis cinerea* by high performance liquid chromatography. *Chin. J. Anal. Chem.* **2006**, *34* (10), 1467−1470.
(13) Tan, J.; Shan, Y. X.; Su, L. Evaluation of SYP-Z048 genotoxicity. *Agrochemicals* **2006**, *45* (4), 269−274.
(14) Yan, W. J.; Li, Z. G.; Zou, L. Y.; Wu, Y. L. Teratogenicity of SYP-Z048 in rats. *Agrochemicals* **2008**, *47* (9), 665−667.
(15) Durand, G.; Barceló, D.; Albaigés, J.; Mansour, M. Utilisation of liquid chromatography in aquatic photodegradation studies of pesticides: A comparison between distilled water and seawater. *Chromatographia* **1990**, *29* (3−4), 120−124.
(16) Espín, S.; Martínez-López, E.; Gómez-Ramírez, P.; María-Mojica, P.; García-Fernández, A. J. Assessment of organochlorine pesticide exposure in a wintering population of razorbills (*Alca torda*) from the southwestern Mediterranean. *Chemosphere* **2010**, *80* (10), 1190−1198.
(17) Bempah, C. K.; Buah-Kwofie, A.; Enimil, E.; Blewub, B.; Agyei-Martey, G. Residues of organochlorine pesticides in vegetables marketed in Greater Accra Region of Ghana. *Food Control* **2012**, *25* (2), 537−542.
(18) Burrows, H. D.; Canle, L. M.; Santaballa, J. A.; Steenken, S. Reaction pathways and mechanisms of photodegradation of pesticides. *J. Photochem. Photobiol., B* **2002**, *67* (2), 71−108.
(19) Lin, Y. J.; Karuppiah, M.; Shaw, A.; Gupta, G. Effect of simulated sunlight on atrazine and metolachlor toxicity of surface waters. *Ecotoxicol. Environ. Saf.* **1999**, *43* (1), 35−37.
(20) Escalada, J. P.; Pajares, A.; Gianotti, J.; Biasutti, A.; Criado, S.; Molina, P.; Massad, W.; Amat-Guerri, F.; García, N. A. Photosensitized degradation in water of the phenolic pesticides bromoxynil and dichlorophen in the presence of riboflavin, as a model of their natural photodecomposition in the environment. *J. Hazard. Mater.* **2011**, *186* (1), 466−472.
(21) Banerjee, K.; Dureja, P. Phototransformation of quinalphos on clay surfaces. *Toxicol. Environ. Chem.* **1998**, *68*, 475−480.
(22) Zhang, L. H.; Xu, C. B.; Chen, Z. L.; Li, X. M.; Li, P. J. Photodegradation of pyrene on soil surfaces under UV light irradiation. *J. Hazard. Mater.* **2010**, *173* (1−3), 168−172.
(23) Scholz, K.; Reinhard, F. Photolysis of imidacloprid (NTN 33893) on the leaf surface of tomato plants. *Pestic. Sci.* **1999**, *55* (6), 652−654.
(24) Bonnemoy, F.; Lavédrine, B.; Boulkamh, A. Influence of UV irradiation on the toxicity of phenylurea herbicides using Microtox® test. *Chemosphere* **2004**, *54* (8), 1183−1187.
(25) Dimou, A. D.; Sakkas, V. A.; Albanis, T. A. Metolachlor photodegradation study in a aqueous media under natural and simulated solar irradiation. *J. Agric. Food Chem.* **2005**, *53* (3), 694−701.
(26) Boesten, J. J.; Köpp, H.; Adriaanse, P. I.; Brock, T. C.; Forbes, V. E. Conceptual model for improving the link between exposure and effects in the aquatic risk assessment of pesticides. *Ecotoxicol. Environ. Saf.* **2007**, *66* (3), 291−308.
(27) Sevilla-Morán, B.; Sandín-España, P.; Vicente-Arana, M. J.; Alonso-Prados, J. L.; García-Baudín, J. M. Study of alloxydim photodegradation in the presence of natural substances: Elucidation of transformation products. *J. Photochem. Photobiol., A* **2008**, *198* (2−3), 162−168.
(28) Mukai, T.; Kumagal, T.; Saiki, H.; Kawamura, Y. Photochemical behaviour of cyclic imino ethers: The N−O bond fission, *syn*−*anti* isomerization and cycloaddition reactions in the C−N−O chromophore. *J. Photochem.* **1981**, *17* (2), 365−368.
(29) Singh, R.; Singh, G.; Ishar, M. P. S. Facile ketone sensitized photochemical ring opening of isoxazolidines to *β*-enaminocarbonyl compounds. *Indian J. Chem.* **2010**, *49B* (2), 234−240.
(30) Cao, Y. S.; Chen, J. X.; Huang, L.; Wang, Y. L.; Hou, Y.; Lu, Y. T. Photocatalytic degradation of chlorfenapyr in aqueous suspension of TiO_2. *J. Mol. Catal. A: Chem.* **2005**, *233* (1−2), 61−66.
(31) Liu, W.; Chen, S. F.; Zhao, W.; Zhang, S. J. Titanium dioxide mediated photocatalytic degradation of methamidophos in aqueous phase. *J. Hazard. Mater.* **2009**, *164* (1), 154−160.
(32) Abramović, B. F.; Banić, N. D.; Šojić, D. V. Degradation of thiacloprid in aqueous solution by UV and UV/H_2O_2 treatments. *Chemosphere* **2010**, *81* (1), 114−119.
(33) Torniainen, K.; Tammilehto, S.; Ulvi, V. The effect of pH, buffer type and drug concentration on the photodegradation of ciprofloxacin. *Int. J. Pharm.* **1996**, *132* (1−2), 53−61.
(34) Evgenidou, E.; Fytianos, K.; Poulios, I. Photocatalytic oxidation of dimethoate in aqueous solutions. *J. Photochem. Photobiol., A* **2005**, *175* (1), 29−38.
(35) Zapata, A.; Oller, I.; Bizani, E.; Sánchez-Pérez, J. A.; Maldonado, M. I.; Malato, S. Evaluation of operational parameters involved in solar photo-Fenton degradation of a commercial pesticide mixture. *Catal. Today* **2009**, *144* (1−2), 94−99.
(36) http://www.sigmaaldrich.com/china-mainland.html.