Aquatic Photodegradation of Albendazole and Its Major Metabolites. 2. Reaction Quantum Yield, Photolysis Rate, and Half-Life in the Environment

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The photolysis rate constant (k_p) of albendazole (ABZ) and its three major metabolites, albendazole sulfoxide (ABZSO), albendazole sulfone ($ABZSO_2$), and 2-aminoalbendazole sulfone ($ABZ2NH_2$), measured in a tube (11 × 100 mm) (see part 1 of this series) will essentially reflect a faster rate than the expected rate (k_{pE}) at the surface of flat water body in the environment. The internal reflections increase the incident sunlight in a test tube. In this experiment, the photolytic reaction quantum yield (Φ) and photolysis rate constant, k_p, measured in a quartz tube were converted to reflect the environmentally relevant rates. A maximum environmental photolysis rate constant (k_{pE}), a minimum half-life, and their respective values for summer and winter seasons for ABZ and its metabolites were estimated.

THEORY

Methods have been developed to measure the photochemical reaction quantum yield (Φ) by exposing an aqueous test solution of a test chemical in a tube to natural sunlight or artificial light (Zepp, 1977; Wolfe et al., 1978). A step-by-step guidance of aquatic photolysis experiments is described elsewhere (Photolysis in Aqueous Solution in Sunlight, 1985; Leifer, 1988).

Reaction Quantum Yield (Φ). The rate of photolysis of a chemical in dilute solution in a flat water body near the surface (k_{pE}) is described by

$$k_{pE} = \Phi_E \sum \epsilon\lambda L\lambda \qquad (1)$$

where Φ_E is the reaction quantum yield of a chemical in dilute solution, which represents the function of photons absorbed that actually affects photolysis and is independent of λ, $\epsilon\lambda$ is the molar absorptivity, and $L\lambda$ is the solar irradiance in water determined over the wavelength range 290–800 nm. The solar irradiance measure will reflect that of a measurement made at shallow depths of a water body under clear sky conditions. The equation provides an environmentally relevant rate constant in aqueous solution as a function of latitude and season of the year.

The sunlight reaction quantum yield for a specific test chemical, $\Phi_E{}^c$, can be calculated using

$$\Phi_E{}^c = (k_p{}^c/k_p{}^a)(\sum \epsilon^a\lambda L\lambda / \sum \epsilon^c\lambda L\lambda)\, \Phi_E{}^a \qquad (2)$$

The term $\sum\epsilon^c\lambda L\lambda$ that describes the light absorbed by the test compound can be calculated using experimentally obtained molar absorptivities ($\epsilon^c\lambda$) and solar irradiance ($L\lambda$) values for respective wavelengths (290–800 nm) as a function of latitude and the season of the year (*Astronomical Almanac*, 1982; Dulin and Mill, 1982). The values for light absorbed by the actinometer, which are described by the term $\sum\epsilon^a\lambda L\lambda$, are tabulated in the *Federal Register* (Photolysis in Aqueous Solution in Sunlight, 1985). $k_p{}^c$ and $k_p{}^a$ are photolysis rate constants of the test chemical and the actinometer, respectively, which are determined experimentally.

An actinometer such as a mixture of *p*-nitroacetophenone and pyridine (PNAP/PYR) can be used to correct for variation in solar irradiance during photoreaction provided that the sample solutions are simultaneously exposed in identical vessels for the same duration (Dulin and Mill, 1982). The rate constant of the actinometer ($k_p{}^a$) can be adjusted by changing the concentration of pyridine.

Making the assumption that the loss of chemical is due only to photolysis, the ratio $k_p{}^c/k_p{}^a$ is determined experimentally by measuring the decrease in concentrations of the test chemical and actinometer as a function of time (t) in sunlight, where

$$\ln (C_0/C_t)^c = (k_p{}^c/k_p{}^a) \ln (C_0/C_t)^a \qquad (3)$$

By plotting $\ln (C_0/C_t)^c$ against $\ln (C_0/C_t)^a$, the slope of the straight line obtained is equal to $k_p{}^c/k_p{}^a$.

The term $\Phi_E{}^a$ is the reaction quantum yield for the actinometer which can be determined as a function of pyridine concentration. The reaction quantum yield ($\Phi_E{}^a$) for the actinometer with a PNAP concentration of 1.00×10^{-5} M is given by the relationship

$$\Phi_E{}^a = 0.0169[\text{PYR}] \qquad (4)$$

where [PYR] is the molar concentration of pyridine.

Maximum Environmental Photolytic Rate Constants and Minimum Half-Lives. The reaction quantum yield ($\Phi_E{}^c$) can be used to predict the maximum photolysis rate constants and minimum half-lives at the flat water body surface under clear sky conditions for any season of the year using

$$k_{pE} = \Phi_E{}^c \sum \epsilon^c\lambda L\lambda \qquad (5)$$

$$t_{1/2} = 0.693/k_{pE} \qquad (6)$$

Similarly, $t_{1/100}$ can be calculated using

$$t_{1/100} = 4.605/k_{pE} \qquad (7)$$

Since photolysis is a useful parameter of the environmental fate of a test substance, the method provides means

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Table I. Determination of Molar Absorptivity ($\epsilon^c\lambda$) and the Sum of Molar Absorptivity Times Solar Irradiance ($\sum\epsilon^c\lambda L\lambda$) for Albendazole[a] at pH 5

wavelength, nm	absorbance[b]			$\epsilon^c\lambda$, M^{-1} cm^{-1}	exposure period values[d]		summer values		winter values	
	1st value	2nd value	mean value		$L\lambda^c$	$\epsilon^c\lambda L\lambda$	$L\lambda$	$\epsilon^c\lambda L\lambda$	$L\lambda$	$\epsilon^c\lambda L\lambda$
297.5	0.0466	0.0464	0.0465	12533.7	3.48E–05	0.44	6.17E–05	0.77	5.49E–07	0.01
300.0	0.0453	0.0457	0.0455	12264.2	1.59E–04	1.95	2.70E–04	3.31	5.13E–06	0.06
302.5	0.0436	0.0436	0.0436	11752.0	5.10E–04	5.99	8.30E–04	9.75	3.02E–05	0.35
305.0	0.0416	0.0411	0.0414	11145.6	1.25E–03	13.93	1.95E–03	21.73	1.19E–04	1.33
307.5	0.0380	0.0382	0.0381	10269.5	2.47E–03	25.37	3.74E–03	38.41	3.38E–04	3.47
310.0	0.0342	0.0341	0.0342	9204.9	4.18E–03	38.48	6.17E–03	56.79	7.53E–04	6.93
312.5	0.0301	0.0302	0.0302	8126.7	6.27E–03	50.95	9.07E–03	73.71	1.39E–03	11.30
315.0	0.0262	0.0259	0.0261	7021.6	8.59E–03	60.32	1.22E–02	85.66	2.22E–03	15.59
317.5	0.0214	0.0216	0.0215	5795.1	1.10E–02	63.75	1.55E–02	89.82	3.19E–03	18.49
320.0	0.0168	0.0168	0.0168	4528.3	1.34E–02	60.68	1.87E–02	84.68	4.23E–02	19.15
323.1	0.0119	0.0119	0.0119	3207.5	2.43E–02	77.94	3.35E–02	107.45	8.25E–03	26.46
330.0	0.0045	0.0051	0.0048	1293.8	8.52E–02	110.23	1.16E–01	150.08	3.16E–02	40.88
340.0	0.0023	0.0020	0.0022	579.5	1.08E–01	62.59	1.46E–01	84.61	4.31E–02	24.98
350.0	0.0017	0.0015	0.0016	431.3	1.21E–01	52.18	1.62E–01	69.87	4.96E–02	21.39
360.0	0.0016	0.0016	0.0016	431.3	1.35E–01	58.22	1.79E–01	77.20	5.68E–02	24.50
370.0	0.0014	0.0013	0.0014	363.9	1.44E–01	52.40	1.91E–01	69.50	6.22E–02	22.63
380.0	0.0010	0.0010	0.0010	269.5	1.54E–01	41.51	2.04E–01	54.99	6.78E–02	18.27
390.0	0.0010	0.0011	0.0011	283.0	1.46E–01	41.32	1.93E–01	54.62	6.33E–02	17.92
400.0	0.0008	0.0007	0.0008	202.2	2.09E–01	42.25	2.76E–01	55.80	9.11E–02	18.42
					$\sum\epsilon^c\lambda L\lambda$ = 860.50		$\sum\epsilon^c\lambda L\lambda$ = 1188.76		$\sum\epsilon^c\lambda L\lambda$ = 292.13	

[a] Concentration of ABZ = 3.71×10^{-6} M. Pathlength = 1 cm. [b] Absorbances at fractional wavelengths were obtained by interpolation from measurements at integral wavelengths. [c] Irradiance ($L\lambda$) values are in millieinsteins per cm^2-day. Values taken from *Astronomical Almanac* (1982), at 40° N latitude. [d] The means of summer and fall values of $L\lambda$ were used for the exposure period values.

Table II. Calculation of Reaction Quantum Yield for Albendazole at pH 5

(A) Test Compound and Actinometer Concentrations (Exposure on October 19, 1988)

sun time, h	albendazole concentration, ppm: 1st value	2nd value	3rd value	mean value	ln (C_0/C_t)	actinometer concentration × 10^{-5} M: 1st value	2nd value	3rd value	mean value	ln (C_0/C_t)
0	0.677	0.626	0.614	0.639	0	1.997			1.997	0
0.5	0.698	0.605	0.591	0.631	0.012070	2.009	2.010	2.020	2.013	–0.00798
1	0.450	0.600	0.585	0.545	0.159118	2.027	2.053	2.049	2.043	–0.02277
2.5	0.384	0.365	0.350	0.366	0.556360	2.004	1.987	1.971	1.987	0.004852
4	0.065	0.081	0.082	0.076	2.129171	1.845	1.788	1.753	1.795	0.106455

(B) Regression Analysis [ln (C_0/C_t)] for Actinometer as X, ln (C_0/C_t) for Compound as Y

intercept	0.299391	slope	16.88005
SE of intercept	0.260930	SE of slope	2.529522
r^2	0.936884	degrees of freedom	3
no. of values	5		

(C) Actinometer Quantum Yield ($\Phi_E{}^a$)

$\Phi_E{}^a$ = 0.0169[PYR] = 0.0169[0.542 M] = 0.009160

(D) Test Compound Quantum Yield ($\Phi_E{}^c$)

$\sum\epsilon^c\lambda L\lambda$ = 388.5 day^{-1} (from EPA tables, mean of summer and fall at 40° N latitude)
$\sum\epsilon^a\lambda L\lambda$ = 860.50 day^{-1} (from previous table)
$\Phi_E{}^c$ = (slope)($\sum\epsilon^a\lambda L\lambda$)($\Phi_E{}^a$)/($\sum\epsilon^c\lambda L\lambda$) = 0.069807

of predicting the persistence of a test substance in the environment. Although there are some uncertainties in the determination of the term $\sum\epsilon^c\lambda L\lambda$, the product of molar absorptivity and solar irradiance being more sensitive to errors in visible absorbance measurement at longer wavelengths, the term partially cancels out in eq 5 that is used to determine k_{pE}.

A computer program, GCSOLAR (Zepp and Cline, 1977), is currently available for prediction of the rate of photoreaction as a function of time of day, day of the year, depth in water, attenuation coefficient of water for natural water bodies, the average ozone layer thickness for this season, locality, latitude, and season.

EXPERIMENTAL PROCEDURES

The preparation of exposure and actinometer solution, determination of UV/visible absorption spectra, exposure to sunlight, sampling, and analysis are described in part 1 of this series. The calculations presented were performed using a Lotus 1-2-3 spreadsheet program.

Photolytic Rate Constant: Measured (k_p) vs Calculated (k_{pE}). The photolysis rate constants measured for aqueous solution of test chemicals in quartz tubes are given in Table I of part 1 of this series. The k_p values in h^{-1} were converted into a daily value by multiplying it by the number of hours between sunrise and sunset of the appropriate dates. The average day length for the period between October 13 and 23, 1988, was 11.22 h. The daily values of k_p were converted into their corresponding rate (k_{pE}) at the flat water surface in the environment by dividing the former by 2.2.

Determination of $\sum\epsilon^c\lambda L\lambda$, $\sum\epsilon^a\lambda L\lambda$, and $\Phi_E{}^a$. The mean of summer and fall solar irradiance ($L\lambda$) values at 40° N latitude for the wavelength range 297.5–400.0 nm was calculated using the values tabulated in the *Federal Register* (Photolysis in Aqueous Solution in Sunlight, 1985).

The product of molar absorptivity ($\epsilon^c\lambda$) and the solar irradiance was summed over the same wavelength range with the mean (summer plus fall) solar irradiance and those for summer and winter seasons. $\sum\epsilon^a\lambda L\lambda$ and $\Phi_E{}^a$ values for the appropriate PNAP/PYR actinometer were obtained from the *Federal Register* (Photolysis in Aqueous Solution in Sunlight, 1985).

RESULTS AND DISCUSSION

A sample calculation of maximum environmental rate constants, half-lives, and their respective values for

Table III. Predicted and Measured Photolytic Rate Constants and Half-Lives for Albendazole at pH 5

(A) Maximum Environmental Photolysis Rate Constants and Minimum Half-Lives

season	seasonal $\sum\epsilon^c\lambda L\lambda$	k_{pE},[a] day^{-1}	$t_{1/2}$,[b] days	$t_{1/100}$,[c] days
summer	1188.8	82.98	0.008	0.055
winter	292.1	20.39	0.034	0.226

(B) Measured Environmental Photolysis Rate Constant and Half-Lives

	k_{pE},[d] day^{-1}	$t_{1/2}$,[b] days	$t_{1/100}$,[c] days
measured values	2.18	0.319	2.12

[a] Calculated $k_{pE} = \Phi_E{}^c \sum\epsilon^c\lambda L\lambda$. [b] $t_{1/2} = 0.693/k_{pE}$. [c] $t_{1/100} = 4.605/k_{pE}$. [d] Measured $k_{pE} = k_p$(sunlight hours)/2.2. $k_p = 0.428\ h^{-1}$ = measured rate constant from Table I of part 1 of this series (independent variable = sun time). Sunrise occurred at 7:25 a.m. EST. Sunset occurred at 6:35 p.m. EST. Sunlight hours = 11.17 h/day.

Table IV. Summary of Calculated Quantum Yields and Measured and Predicted Photolytic Rate Constants for Albendazole and Its Metabolites

test compd	pH	calcd quantum yield, $\Phi_E{}^c$	measd rate constant, k_{pE}, day^{-1}	predicted rate constant, k_{pE}, day^{-1}: summer value	winter value
ABZ	5	0.070	2.18	83.0	20.4
	7	0.094	1.60	61.8	12.0
	9	0.076	4.21	157	42.3
ABZSO	5	0.046	1.21	5.34	0.91
	7	0.106	1.39	6.44	0.66
	9	0.150	2.66	20.2	2.99
$ABZSO_2$	5	0.0012	0.38	1.42	0.39
	7	0.022	0.97	3.17	0.64
	7	0.034[a]	0.97	4.78[a]	0.97[a]
	9	0.188	6.00	48.6	9.02
$ABZ2NH_2$	5	0.0066	0.16	1.77	0.42
	7	0.014	0.32	3.60	0.71
	9	0.072	0.37	4.28	0.42

[a] These values are calculated using a least-squares regression. The concentration measurements for the 2.25-h samples have been omitted due to aberrant values.

summer and winter months for a solution of ABZ at pH 5 are presented below.

Reaction Quantum Yield ($\Phi_E{}^c$). The reaction quantum yield for ABZ solution at pH 5 was calculated using eq 2; the $L\lambda$ and $\sum\epsilon^c\lambda$ data and the product $\sum\epsilon^c\lambda L\lambda$ are given in Table I. The calculation of reaction quantum yield is given in Table II. The maximum photolytic rate constant and minimum half-life calculated for ABZ in winter and summer seasons are given in Table III. The measured photolytic rate constant corrected to an environmentally relevant rate (k_{pE}), $t_{1/2}$, and $t_{1/100}$ values are also given in Table III.

The photolytic rate constants at the flat water body surface (measured and predicted) are summarized in Table IV. The predicted values are calculated for clear sky conditions at 40° N latitude.

Theoretically, since the sunlight exposure took place in late summer to early fall, experimentally measured values of half-lives should fall within the values predicted for summer and winter under clear sky conditions. As expected, the majority of $t_{1/2}$ values for ABZSO and $ABZSO_2$ (Table V) fall within the predicted summer and winter values as the experiment was conducted under clear sky conditions. This is not the case for ABZ and $ABZ2NH_2$, since adverse weather conditions prevailed during exposure.

Table V. Summary of Measured and Predicted Half-Lives and $t_{1/100}$ for Albendazole and Its Metabolites

test compd	pH	$t_{1/2}$, days: measd value	predicted summer value	predicted winter value	$t_{1/100}$, days: measd value	predicted summer value	predicted winter value
ABZ	5	0.319	0.008	0.034	2.12	0.055	0.226
	7	0.434	0.011	0.058	2.88	0.074	0.383
	9	0.165	0.004	0.016	1.10	0.029	0.109
ABZSO	5	0.572	0.130	0.759	3.80	0.862	5.04
	7	0.499	0.108	1.05	3.32	0.715	6.98
	9	0.261	0.034	0.232	1.73	0.227	1.54
$ABZSO_2$	5	1.83	0.487	1.77	12.2	3.24	11.8
	7	0.715	0.218	1.08	4.75	1.45	7.16
	7	0.715	0.145[a]	0.714[a]	4.75	0.963[a]	4.75[a]
	9	0.116	0.014	0.077	0.768	0.095	0.511
$ABZ2NH_2$	5	4.28	0.391	1.65	28.5	2.60	11.0
	7	2.18	0.193	0.973	14.5	1.28	6.47
	9	1.88	0.162	1.67	12.5	1.08	11.1

[a] These values are calculated using a least-squares regression from which the 2.25-h concentration measurements have been omitted.

The measured and predicted half-lives and the time required for a test substance to degrade to 1% of the starting concentration are given in Table V. Once again, the predicted values are for clear sky conditions in summer and winter seasons.

Conclusions. Albendazole appears to be the most susceptible to photolysis in solutions, with 50% of the starting material degrading under clear sky conditions in less than 1 day even in winter. According to the predicted values of photolytic rates based on quantum efficiencies of light, albendazole and its three major metabolites undergo rapid degradation with half-lives of less than 1 day in midsummer and of less than 2 days in midwinter. The majority of the measured half-lives for ABZSO and $ABZSO_2$ fall within or close to their predicted values for summer and winter, indicating that the experiment provides a good estimation of photolytic rates under different seasons. The measured half-lives of ABZ and $ABZ2NH_2$ are higher than the predicted values as expected, since the exposure of these chemicals took place under inclement weather conditions.

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