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Original article

Mercury Catalyzed the Hydrolysis of Quinalphos

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ABSTRACT

Hydrolysis of the organophosphorothioate compound, quinalphos (Q, O,O-diethyl O-quinoxaline-2-yl phosphorothioate) in the presence of Hg2+ was investigated at 25oC and pH 4.0, 7.0 and 10.0 using HPLC with UV detection. The hydrolysis products were 2-hydroxyquinoxaline (HQ) and O,O-diethyl phosphorothioic acid (PA). The kinetic results show clearly that mercury ion catalyzed the hydrolysis of Q, as the catalytic rate increased by presence of Hg2+. The maximum kobs was observed at the lowest pH value (pH 4.0). In the second part of this work, Electrospray ionization mass spectrometry (ESI-MS) technique was used to study how Hg2+ coordinates the substrate (Q) in ways that accelerate hydrolysis. [(PA)2 + Na + Hg]+ complex was formed; this indicates that the binding takes place between Hg2+ and the S atom.

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INTRODUCTION

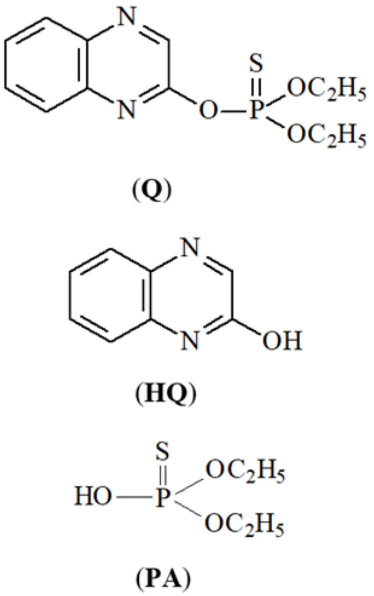
Hydrolysis of organophosphorus compounds has been investigated by several researchers [1-9]. A number of studies have shown that dissolved metal ions play an important role in catalysis of the hydrolysis of OP compounds [10-15]. Catalysis of the hydrolysis of OP compounds by metal ions depends on the metal ion itself, the substrate, and the possible interactions between the metal ion and the substrate. The first study on the effect of metal ions on the hydrolysis of OP compounds was reported in 1956 by Ketelaar et al. [11]. They found that under slightly alkaline conditions (pH between 7.8 and 8.6), the hydrolysis of parathion, paraoxon, and thionobenzene phosphoric acid O-ethyl-O-P-nitrophenylester (EPN) was catalyzed by Cu2+.

Hg2+ has catalytic effect on the hydrolysis of OP compounds. As an example, parathion methyl, Malathion, Fenitrothion, Fenthion were catalyzed by Hg2+ [14]. On the other hand, Hg2+ was found to have little effect on the hydrolysis of dichlorvos [14]. Unlike the other OP compounds in that study, dichlorvos does not contain a sulfur atom in its structure and it is postulated that catalysis by Hg2+ is associated with its strong preference for S-containing ligands.

Hydrolysis of quinalphos at different pH values (pH, 11.8 – 13.6) and different temperatures (25, 35, 45oC) was studied in our laboratory [8]. Activation parameters (ΔH‡, ΔS‡, and ΔG‡) were also determined [8]. In another recent work, we have also studied effect of separately solids (MnO2 and TiO2) on the hydrolysis of quinalphos at pH 4.0, 7.0, and 10.0 and temperature 25oC [9]. More recently, Cu2+ was found to significantly increase the hydrolysis rate of quinalphos at different pHs [10].

Electrospray ionization mass spectrometry (ESI-MS) has been widely used in studying metal complexes [16]. Interactions between metal ions and organic compounds have been studied by a number of groups [10,17-22]. For example, Williams et al. [20] have studied metal-macrocycle binding by using ESI-MS. Hg2+-macrocycles complexes were observed, indicating that Hg2+ binds to S. In another ESI-MS study, the ability of Ag+ and Hg2+ to form complexes with bis-tren(tris-pyridine) amine and bis-tren(tris-pyridine) phenylamide, both of which contain N in their structures was investigated [21]. In another more recent paper and by using ESI-MS technique, we have observed $[Q + Cu]^+$ and [Cu + HQ] + complexes [10].

The Q molecule contains two possible sites, sulfur and nitrogen atoms that are potentially available for binding transition metal ions. Because Hg2+ has different affinity toward sulfur and nitrogen binding sites, it was chosen for examination in this study. Chemical structure of Q, HQ, and PA are shown figure 1.


(Q)

(HQ)

(PA)

Figure 1: Figure 1 chemical structure of quinalphos (Q), 2-hydroxyquinoxaline (HQ), and O,O-diethyl phosphorothioic acid (PA)

MATERIAL AND METHODS

Q, HQ, and PA

Quinalphos (Q, O,O-diethyl O-quinoxaline-2-yl phosphorothioate, C12H15N2O3PS, 99.8 %) and its hydrolysis product (2-hydroxyquinoxaline, HQ, C8H6N2O, 99 %) were obtained from Crescent Chemicals, U.S.A. Both were of the highest purity available and were used as received. A sample of the second product (O,O-diethyl phosphorothioic acid, PA, C4H11O3PS) was prepared at Queen's University as described by Pieda [5]. The stock solutions of quinalphos and O,O-diethyl phosphorothioic acid were prepared individually in 1,4-dioxane, both with a concentration of 3.38 x 10-2 mol L-1. Due to low solubility of the other product (2-hydroxyquinoxaline) in 1,4-dioxane, it was prepared in dimethyl sulfoxide, DMSO, with a concentration of 2.40 x 10-2 mol L-1. 1,4-Dioxane was purified by reflux over anhydrous stannous chloride for at least 5 hours followed by distillation to remove peroxide [23]. The purities of Q, HQ, and PA were verified by ESI-MS and nuclear magnetic resonance (NMR, 500 MHz).

Mercury solution

A mercury solution was prepared by dissolving 0.0021 g of mercury (Hg) metal (Engelhard Company) in concentrated nitric acid (0.5 mL) and transferred to a 1.00 L volumetric flask and diluted with DDW to the mark. The concentration of this solution was 1.00 x 10-5 mol L-1.

Ethylenediaminetetraacetic acid (EDTA)

A weighed quantity of EDTA disodium salt, C10H14N2Na2O8.2H2O, EDTA (Anachemia Chemicals, Canada) was dissolved in DDW and diluted up to 500 mL with the same solvent. 4.08 x 10-5 M was the concentration of this solution.

Kinetic studies

Experiments were performed in duplicate in clear glass vials (28 x 95 mm) sealed with Teflon-lined screw caps. Reaction solutions (25 mL) were continuously shaken using a shaker bath (Precision Scientific Company, Model 25) set at 100 oscillations / min, at 25oC. As the solution pH may affect the catalytic ability of the metal ions, determinations were conducted at different pH values, 4.0, 7.0, and 10.0. The reaction rate of quinalphos hydrolysis was determined at the three pH values in the presence of 0.01 mmol L-1 of Hg2+. However, hydrolysis of quinalphos in the presence of Hg2+ at pH 4.0 was observed to be very fast. Therefore, a method was employed to quench the reaction at sampling time before injection to a Varian High-Performance Liquid Chromatography (HPLC) with UV-Visible detection. Details of this technique can be found in reference 9. Quenching was performed by adding sufficient EDTA (a 2:1 molar ratio of EDTA:Hg2+) in order to ensure that there was no reaction after sampling and during HPLC analysis. As described above, a stock reaction solution was prepared (Hg(NO3)2, with pH adjusted to 4.0, and then Q was injected to initiate the reaction. An aliquot (0.4 mL) was removed from this reaction vial every 90 sec. and transferred to separate analysis vials. To each sample, the EDTA solution (0.2 mL) was added. These samples were then analyzed by HPLC.

Control experiments, however, were carried out under the same conditions of pH, temperature, and concentration of substrate in order to follow hydrolysis in the absence of any metal ion. The progress of the reactions was determined by measuring concentrations of both Q and HQ, employing the same technique, HPLC.

ESI-MS Analysis

ESI-MS was used to investigate the species generated from Q, HQ, or PA with Hg2+. For ESI-MS measurements, in the case of quinalphos, samples were prepared having the same pH (4.0), concentration of the metal ion (Hg2+), and concentration of quinalphos as in the kinetic experiments. Other experiments were performed under the same conditions but using the hydrolysis products (HQ or PA) in place of the Q. In these experiments, the concentrations of HQ and PA were 3.36 x 10-5 and 3.38 x 10-5 mol L-1, respectively, and the mercury ion concentration was the same as above. Quinalphos was mixed with Hg2+ solution just prior to the MS measurement in order to minimize the extent of hydrolytic degradation. All spectra were first acquired in the positive ion mode. However, in the case of HQ, the negative ion mode was also used.

RESULTS AND DISCUSSION

Hydrolysis of quinalphos in the presence of Hg2+

Hydrolysis of quinalphos was studied by following disappearance of Q as well as appearance of HQ product, using LC with UV detection at 240 nm. Our results show that Hg2+ catalyzed the hydrolysis of quinalphos, as the hydrolysis rates in the absence of

Hg2+ were determined to be 6.75 ◎ 0.11 x 10-8, 9.50 ◎ 0.17 x 10-8, 17.6 ◎ 0.0 x 10-8 s-1 at pH 4.0, 7.0, and 10.0, respectively comparing to the rates in Table 1. Hydrolysis data for quinalphos in the absence and presence of Hg2+ is illustrated in a typical plot (Figure 1). Kinetic data for the hydrolysis of quinalphos at 25oC and different pH values can be found in Table 2. The error in kobs values is expressed as the average deviation of two independent measurements.

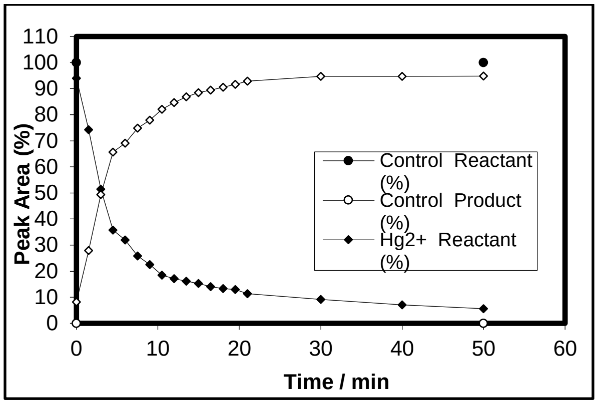


Figure 2. Typical plot showing effect of Hg2+ on the hydrolysis of quinalphos in unbuffered solutions at pH 4.0

Table 1 Kinetic data for the hydrolysis of quinalphos in the presence of Hg^{2+} at $25^{o}C$

pH	kobs (dis) x 103, s-1	kobs (app.) x 103, s-1	kobs (avg) x 103, s-1
4.0	3.63 ± 0.02	3.67 ± 0.02	3.65 ± 0.02
7.0	0.207 ± 0.002	0.182 ± 0.002	0.195 ± 0.013
10.0	0.003 ± 0.000	0.003 ± 0.000	0.003 ± 0.000

*k_{obs} (dis) = First order rate constant (disappearance of quinalphos, **Q**). k_{obs} (app.) = First order rate constant (appearance of the product, **HQ**). k_{obs} (avg) = Average first order rate constant*

Catalysis by Hg2+- Effect of pH

In this paper, table 1 lists the first order rate constants for the disappearance of Q and appearance of HQ as determined from standard first-order plots. Figure 1 and table 1 show clearly that Hg2+ catalyzed the hydrolysis of quinalphos at pH 4.0, 7.0, and 10.0. In fact, addition of Hg2+ (0.01 mmol L-1) yields significant catalysis of quinalphos hydrolysis over a wide pH range as shown in Figure 2. Furthermore, the comparable constants for appearance of HQ are also in reasonable accord. An average rate constant value, kobs (avg), is also given in Table 1. It can be seen from table 1 that in the presence of Hg2+ the maximum kobs was observed at the lowest pH value (pH 4.0), whereas the smallest kobs was recorded at the highest pH (pH 10.0). The error in kobs values is expressed as the average deviation of two independent measurements.

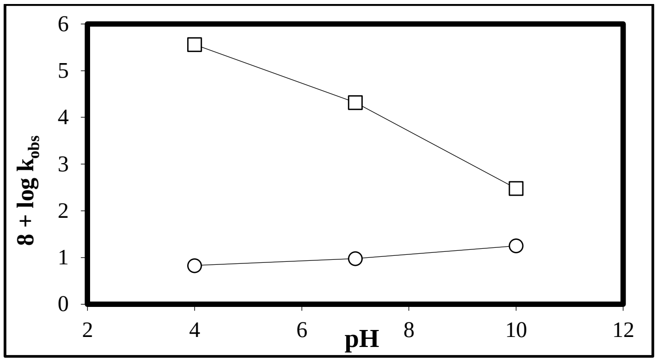


Figure 2. Effect of pH on catalysis of the hydrolysis of quinalphos (disappearance of quinalphos) in the absence and presence of Hg2+.

It can be seen also from table 1 and figure 2 that the maximum rate in the presence of Hg2+ was found at the lowest pH value (pH 4.0). This is in agreement with previous studies on the hydrolysis of other OP compounds in the presence of Hg2+ [24,25]. Zeinali and Torrents have investigated the hydrolysis of parathion-methyl over the pH range 3.5 - 5.5 in the presence of Hg2+ and found that the maximum rate was observed at the lowest pH [25]. In another study, Wan et al. have also reported the maximum kobs at the lowest pH for hydrolysis of other organophosphorus compounds (fenitrothion, fenthion, malathion, and parathion-methyl) in the presence of Hg2+ at different pH values that fall within acidic to slightly basic region (i.e., 5.5 ◎ pH ◎ 7.5) [24].

On the other hand, the lowest rate in the presence of Hg2+ was observed at the highest pH (pH 10.0) (Table 1 and Figure 2). The decrease of the activity of mercury ion at pH 7.0 and 10.0 in reacting with Q is probably due to deprotonation of Hg2+ aquo complexes. As a consequence, at pH 7.0 and 10.0, Hg exists primarily in the form of Hg(OH)2(H2O)2. It appears that this species is less able to complex with quinalphos and is for this reason, a less efficient catalyst

ESI-MS Studies

As the hydrolysis of Q catalyzed by presence of Hg2+, which most probably related to the interaction between the metal ion and the substrate, ESI-MS was chosen to investigate the possibilities of complexation between Hg2+ and Q, HQ, or PA. The purpose of doing this work is: If there is evidence of interaction between Hg2+ and the PA part of the molecule, this might indicate that the metal ion coordinates the S atom. If, however, a complex involving the HQ part of the molecule and the Hg2+ is observed, then this may be an indication of binding taking place at N.

ESI-MS analyses were performed in the absence and presence of Hg2+. All spectra were first acquired in the positive ion mode. However, when positive ion mode did not provide useful results, the negative ion mode was also used.

ESI-MS in the presence of Hg2+

Mercury containing ions can be recognized readily by the isotopic pattern of Hg (196Hg, 198Hg, 199Hg, 200Hg, 201Hg, 202Hg, and 204Hg, with natural abundance of 0.14, 10.02, 16.84, 23.13, 13.22, 29.80, and 6.85, respectively [26]; all the isotopes except 196Hg would be expected to be visible). In a solution containing quinalphos (Q) and Hg2+, a variety of ions were identified corresponding to [HQ + H]+, [Q + H]+, [Q + Na]+, and [(PA)2 + Na + Hg]+ (Table 2 and Figure 3), but there were no ions ascribable to the parent compound, Q, complexed to mercury. Recall that the rate of hydrolysis of Q in the presence of Hg2+ at pH 4.0 is very rapid and therefore no ◎Q + Hg◎2+ ion or any other ion involving quinalphos and mercury was seen. This does not preclude formation of a complex of Q and Hg2+, but rather suggests that as soon as any complex formed, it rapidly decomposes.

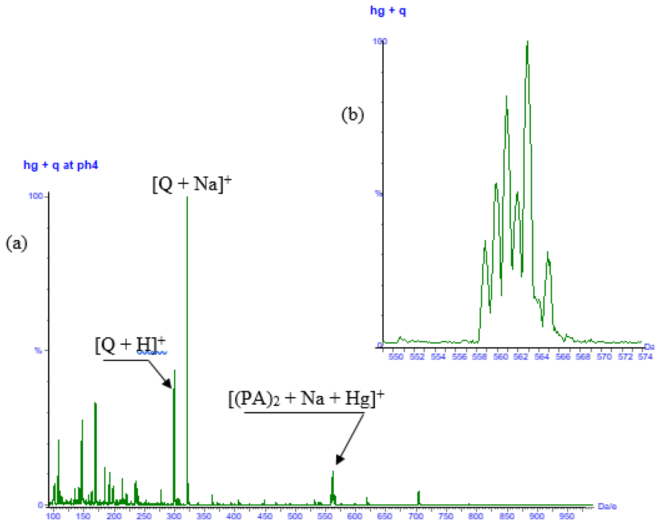


Figure 3 (a) Positive ion ESI mass spectrum of unbuffered aqueous solution containing 33.8 🐦M quinalphos and 10 🐦M Hg2+. (b) The expanded region contains peak corresponding to 🐦(PA)2 + Na + Hg🐦+ ion.

Table 2 Interpreted ESI-MS data from the interaction of quinalphos with Hg2+

Concentration of Q	Concentration of Hg2+	Ions at m/z*	Identification of Ions
3.38 x 10-5 mol L-1	1.0 x 10-5 mol L-1	147 299 321 563	[HQ + H]+ [Q + H]+ [Q + Na]+ [(PA)2 + Na + Hg]+

** In this table the mass of ion containing mercury is calculated in terms of 202Hg.*

Figure 3 and Table 2 show the presence of a peak corresponding to mercury combined with the sulfur-containing hydrolysis product [(PA)2 + Na + Hg]+, providing evidence that binding most likely occurs through the S atom. The observed [(PA)2 + Na + Hg]+ ion has a single positive charge because the two PA molecules are deprotonated and therefore carry one negative charge each.

The interaction of HQ and PA with Hg2+ was also examined. The electrospray mass spectrum of HQ in the presence of Hg2+ shows that there is no evidence of complexation between HQ and Hg2+ in the positive ion mode spectrum. The negative ion mode spectrum shows a peak for ◎HQ - H◎- at m/z 145 (Figure 4). On the other hand, in Figure 5, a peak is seen at m/z 563, showing that a [(PA)2 + Na + Hg]+ ion is formed, which is again evidence of the ability of mercury to combine with the S.

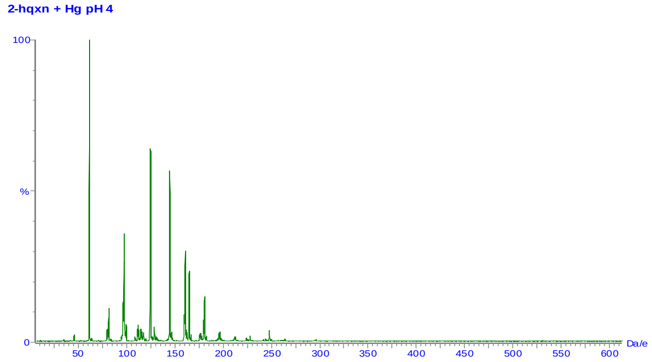


Figure 4. Negative ion ESI mass spectrum of unbuffered aqueous solution containing 33.6 μM 2-hydroxyquinoxaline and 10 μM Hg2+.

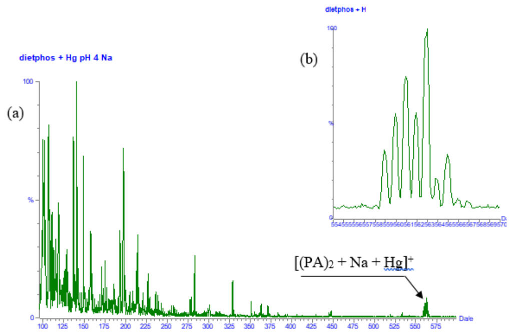


Figure 5 (a) Positive ion ESI mass spectrum of unbuffered aqueous solution containing 33.8 μM O,O diethylthiophosphorothioic acid and 10 μM Hg^{2+}. (b) The expanded region contains peak corresponding to [(PA)$_2$ + Na + Hg]$^+$ ion.

The ESI-MS data of the products (HQ and PA) in the presence of Hg2+ indicate that Hg2+ is able to form an identifiable complex with PA but not with HQ. This may be interpreted as being a consequence of mercury having greater affinity toward ligands containing sulfur compared with those containing nitrogen.

An interesting observation is the fact that no complex was seen for Q with mercury (Table 2 and Figure 3). However, a peak corresponding to mercury combined with the sulfur-containing hydrolysis product [PA2 + Na + Hg]+ was detected (Table 2 and Figures 3 and 5). This likely indicates that binding occurs predominantly through the S atom. In a related study in our laboratory, diazinon and fenitrothion, both P = S compounds, Hg2+ have been found also to form complexes with the sulfur-containing hydrolysis products [27].

CONCLUSION

Hydrolysis of quinalphos was studied in the absence and presence of Hg2+ at pH 4.0, 7.0, and 10.0 and temperature 25oC, using HPLC/ UV technique. It is clear that Hg2+ catalyzed the hydrolysis of Q by increasing the hydrolysis rates. Reaction rate constant was found to be decreased with increasing pH. That is due to the presence of insoluble hydroxy species of this metal ion.

In the ESI-MS results, a Q - Hg complex was not observed, that is because of the very rapid catalysis in the presence of Hg2+. However, a complex involving Hg2+ and PA (◎PA + Na + Hg◎+) was produced through fragmentation. The same ion was also observed in solutions containing Hg2+ and authentic PA compound, but no ion was observed involving Hg2+ and HQ. Based on these results, it is suggested that Hg2+ binds to Q through the S atom. This increases the susceptibility for nucleophilic attack by H2O or OH- and thus enhances the hydrolysis rate.

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Conflict of Interest

The authors declare no conflict of interest.

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