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Unprecedented Treatment Strategy of Aquatic Environments: Oxidative Degradation of Penicillin G by Chromium Trioxide in Acidic Media and the Impact of Metal Ion Catalysts: Kinetics and Mechanistic Insights

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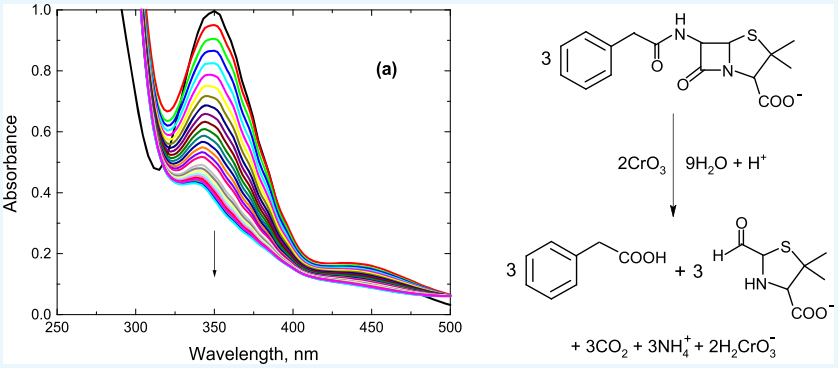

ABSTRACT: Degradation kinetics and pathways of the antibiotic penicillin G (Pen) have been examined via oxidation by chromium trioxide (Cr^{VI}) in aqueous sulfuric and perchloric acid media. The oxidation reactions were monitored by spectrophotometry at 298 K. In both acidic media, penicillin G oxidation was set to proceed through acid catalysis. The stoichiometry of the reactions designated that 3 moles of Pen required 2 moles of Cr^{VI}. The kinetics of Pen oxidation in both acids was of the first order with regard to [Cr^{VI}] and less-than unity order with regard to [Pen] and [H^+] in their variation. The rates of reactions displayed negligible impacts upon altering ionic strengths or dielectric constants of the reaction media. There was no intrusion of free radicals throughout the redox reactions. Addition of low concentrations of Ni^{2+}, Cu^{2+}, and Zn^{2+} ions enhanced the oxidation rates, while addition of Cr^{3+} as a described product did not noteworthily alter the rates. Under comparable investigational circumstances, the oxidation rates in $HClO_4$ were almost 2-fold greater than in H_2SO_4. The oxidation products of penicillin G were identified by spectral analysis and spot tests as phenyl acetic acid, 2-formyl-5,5-dimethyl-thiazolidine-4-carboxlate ion, ammonium ion, and carbon dioxide. Reliance of reaction rates on temperature has been explored, and the activation and thermodynamic parameters were estimated and debated. In view of the noted reactions' orders and products' identification, a plausible mechanism for the oxidation reactions was suggested. The derived rate law was set to be in accordance with the acquired results. This study offers an unprecedented simple and low-cost treatment method for removal or degradation of certain pollutants for protecting the environment and human health.

INTRODUCTION

Great amounts of pharmaceuticals are produced for human and veterinary healthcare and food and pharmaceutical industries. Antibiotics are among the supreme significant collections of pharmaceuticals utilized for remediating human and animals from bacterial and fungal diseases. Penicillins are a group of β-lactam antibiotics and are regarded as the greatest potent and successful accomplishments in the recent decades.[1] They were among the first antibiotics to be efficient against numerous bacterial infections resulting from staphylococci and streptococci. Penicillin G (Pen) or benzylpenicillin is noticed to have efficiency primarily against Gram-positive organisms, which is used to remediate certain bacterial infections. It was reported[2] that, when antibiotics are taken by oral, only 10−20% is metabolized, while the remainder, 80−90%, is excreted by the human or animal body into the environment. In addition, large quantities of antibiotic residues are generated

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daily from hospitals and pharmaceutical industries. Consequently, such antibiotic excreta and residues reach easily surface and ground water,[3] which may be pharmacologically active, inactive, or toxic materials. Arrival of these materials to aquatic environments and their persistence for long periods can result in their vast bio-accumulation in the environment leading to toxic effects on the soil, water resources, and natural life[4] because these materials contain complex, stable, and non-biodegradable organic compounds, which have potential adverse impacts on aquatic ecology and human health. Also, these materials kill the ecological microorganisms essential for biological treatment of wastewater. Thus, these materials are very dangerous pollutants for the ecological system and human health.[3] Therefore, removal or degradation studies of antibiotics in aqueous media became part of significant environmental research.[5−9] Conventional treatment technologies of pharmaceuticals pollution based on biological treatment are ineffective ways for removal of such harmful materials from water sources.[10,11] Nevertheless, chemical oxidation is a noteworthy manner for antibiotics degradation in aqueous media.[5−8] Oxidation of pharmaceutical drugs[12−16] plays a chief role in water treatment methods or in understanding drug metabolism in pharmacokinetic investigation. Chemical oxidation is considered as a more believable strategy for degradation of pharmaceutical drugs in wastewater and surface and ground water. During the oxidation process, the oxidizing agent converts the toxic chemicals to less toxic ones, which are safe to be discharged into the environment.

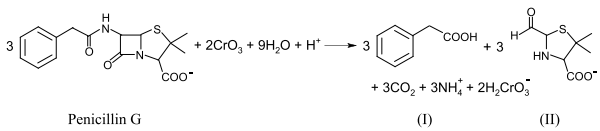
Chromium(VI) ions are deliberated as powerful oxidizers that play a considerable function in biomolecule chemistry owing to the mutagenic and carcinogenic reactivities of chromium compounds.[17,18] One of the noteworthy Cr^{VI} compounds is chromium trioxide ($Cr^{VI}O_3$), which is the acidic anhydride of chromic acid ($H_2Cr^{VI}O_4$).[19] It is also a robust multi-electron oxidizing agent employed in organic synthesis.[21−24] It is a highly toxic and carcinogenic compound although the corresponding Cr^{III} derivatives are comparatively non-toxic[20] and they are essential in human nutrition. Consequently, various reductants are used to transform toxic chromium(VI) compounds into safe chromium(III) compounds. A literature survey illuminated that a variety of studies were published on chromic acid oxidation of distinctive inorganic[25,26] and organic[27−33] compounds, whereas there are not much reports about oxidation by chromium trioxide.[21−24]

Antibiotics are known to construct complexes with metal ions since they are organic compounds containing various electron-donating atoms in their chemical structures able to coordinate with metal ions yielding mono-, di-, and polynuclear metal complexes.[34−37] Studies of the complexation of antibiotics as biologically active ligands with metal ions have lately attracted respectable interest because of their significant impacts on the therapeutic action of antibiotics and their wide utilization in medicine, pharmaceuticals, and cosmetics.[34] This can be interpreted on the basis of the increased antimicrobial activities of antibiotics upon their complexation with certain metal ions.[38] Additionally, such complexation can be employed in the determination of antibiotics in samples[39] and in the removal of the some metal ions from an organism.[40]

On the other hand, in biochemical reactions, knowledge of the kinetics of pharmaceutical drugs is referred to optimization of the reaction circumstances for illuminating a perfect mechanistic image of drug metabolism. In some cases, the rate constants of the oxidation processes between drug molecules and oxidants may illuminate the activity of such molecules toward the treatment method and can be useful in modeling such a method.[12] A careful literature review indicated that very little kinetic studies have been reported on the removal or degradation of penicillin G antibiotic in aqueous media.[41,42] In light of very lacking literature on the kinetics of oxidative degradation of penicillin G as well as little reported studies on the utilization of chromium triode as an oxidant especially for potential degradation of pharmaceutical pollutants, the present detailed study was explored. In the present investigation, we are reporting kinetics, pathway, and thermodynamic features of the degradation of penicillin G (Pen) by chromium trioxide in different acidic media. The principle objectives of this study were to explore the choosiness of penicillin G toward chromium trioxide oxidant, investigate the impact of the kind of acidic medium on the reactions' kinetics, propose a plausible oxidation pathway, and derive the rate-law expression agreeing with the investigational kinetic outcomes. This investigation introduces a hopeful method with a dual benefit for the environment and human health: degradation of penicillin G antibiotics and conversion of the highly toxic and carcinogenic chromium trioxide to a non-toxic chromium(III) compounds. This treating technique may be simple and low-cost, which recommends more benefit for the environment and human health.

RESULTS

Stoichiometry and Product Characterization. Several reaction sets with different ratios of $[CrO_3]/[Pen]$ at fixed $[H^+]$ and I at 298 K were allowed to interact until achievement of the reactions. Spectrophotometric assessment of unreacted $[CrO_3]$ in both acidic media designated that two moles of CrO_3 react with three moles of Pen to construct the oxidation products as illustrated by the equation,



(1)

The above equation is in full accordance with product identification where the oxidation products I and II were identified by FT-IR spectroscopy as phenyl acetic acid and the 2-formyl-5,5-dimethyl-thiazolidine-4-carboxlate ion, respectively. FT-IR spectra of both penicillin G and its oxidation products are illustrated in Figure S1a,b, respectively (in the Supporting Information). Figure S1b reveals disappearing of the absorption band found at about 1780 cm^{-1} (for amidic ketone C═O stretch) in the penicillin spectrum; Figure S1a. Figure S1b illustrates the development of a broad band at about 3370 cm^{-1} corresponding to carboxylic OH with N−H stretching, which is in accordance with the oxidation product 5,5-dimethyl-thiazolidine-2,4-dicarboxlate ion. Also, the band which appeared at about 1630 cm^{-1} corresponds to carboxylic C═O stretch. The byproducts were identified as NH_4^+ and CO_2 as described elsewhere.[43] Moreover, the establishment of Cr^{III} was emphasized by the rebate in the reactions' rates after addition of Mn^{II} ions to the reaction sets.[26,33]

Time-Resolved Spectra. Spectral changes recorded for penicillin G oxidation by chromium trioxide in both sulfuric and perchloric acid solutions are presented in Figure 1a,b, respectively. The scanned spectra showed a regular vanishing of the Cr^{VI} band at λ = 348 nm with advancing the reactions due to the reduction of Cr^{VI} to Cr^{III} ion by penicillin G. It is

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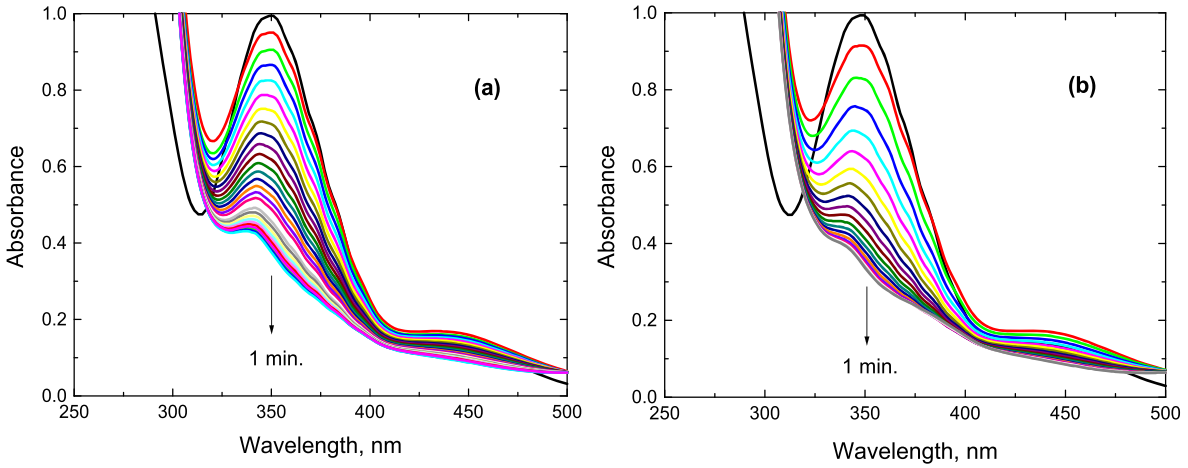

Figure 1. Time-resolved spectra for the oxidative degradation of penicillin G by CrO_3 in (a) H_2SO_4 and (b) $HClO_4$ media. [Pen] = 2.0×10^{-2}, [Cr^{VI}] = 5.0×10^{-4}, [H^+] = 1.0, and I = 2.0 mol dm^{-3} at 298 K.

Table 1. Effect of [Cr^{VI}], [Pen], [H^+], and I on the Values of k_{obs} in the Oxidative Degradation of Penicillin G by CrO_3 in H_2SO_4 and $HClO_4$ Media at 298 K[a]

10^4 [Cr^{VI}] (mol dm^{-3})	10^2 [Pen] (mol dm^{-3})	[H^+] (mol dm^{-3})	I (mol dm^{-3})	sulfuric (10^3 k_{obs} s^{-1})	perchloric (10^3 k_{obs} s^{-1})
1.0	2.0	1.0	2.0	6.9	12.9
3.0	2.0	1.0	2.0	7.3	13.9
5.0	2.0	1.0	2.0	7.1	13.8
7.0	2.0	1.0	2.0	7.2	13.6
9.0	2.0	1.0	2.0	6.8	14.2
5.0	1.0	1.0	2.0	3.9	9.0
5.0	2.0	1.0	2.0	7.1	13.8
5.0	3.0	1.0	2.0	9.9	17.1
5.0	4.0	1.0	2.0	13.2	20.9
5.0	5.0	1.0	2.0	15.6	23.8
5.0	2.0	0.2	2.0	1.8	4.1
5.0	2.0	0.6	2.0	4.5	9.4
5.0	2.0	1.0	2.0	7.1	13.8
5.0	2.0	1.4	2.0	10.2	18.1
5.0	2.0	1.8	2.0	12.3	22.2
5.0	2.0	1.0	2.0	7.1	13.8
5.0	2.0	1.0	2.5	7.5	12.7
5.0	2.0	1.0	3.0	7.4	12.9
5.0	2.0	1.0	3.5	7.2	13.4
5.0	2.0	1.0	4.0	6.9	13.5

[a]Experimental error ± 4%.

easy to observe that such vanishing occurred in $HClO_4$ and is significantly faster than that in H_2SO_4.

Impact of [Cr^{VI}] on the Degradation Rates. The impact of varying the concentration of the chromium trioxide oxidant [Cr^{VI}] (1.0×10^{-4} to 9.0×10^{-4} mol dm^{-3}) was illuminated in both acidic solutions at fixed [Pen], [H^+], and I. It was noticed that graphs of ln Abs. vs time (see Figure S2 in the Supporting Information) gave good straight lines and the values of k_{obs} were set to be free of the started [Cr^{VI}] as listed in Table 1. Such investigational outcomes specified that the oxidation rates are not credent of [Cr^{VI}] and the reaction order with regard to the oxidant is set to be one.

Impact of [Pen] on the Degradation Rates. The oxidation rates were carried out at dissimilar concentrations of the penicillin G reductant, [Pen], at four temperatures retaining the concentrations of other constituents firm. The acquired outcomes designated that raising [Pen] increased the oxidation rates as noted from the values of k_{obs} in Table 1. Graphs of k_{obs} vs [Pen] at various temperatures were clearly linear with positive intercepts as illustrated in Figure 2 emphasizing that the orders of the redox reactions in both acidic media with regard to [Pen] are less than unity, namely, $0 < n < 1$ (as seen from the slopes of log k_{obs} vs log [Pen] graphs illustrated in the Supporting Information as Figure S3).

Impact of [H^+] on the Degradation Rates. The impact of [H^+] on the rates of the oxidation reactions was explored in order to illuminate some aspects in the oxidation mechanism. In this regard, kinetic measurements were determined at several [H^+] values (0.2−1.8 mol dm^{-3}) with sulfuric and perchloric acids keeping all other variables stable. Augmented acid concentrations were set to enhance the oxidation rates (Table 1). This means that the existing oxidation reactions are acid-catalyzed. Graphs of k_{obs} versus [H^+] were linear with noteworthy positive slopes emphasizing fractional first-order credence according to [H^+] (Figure 3). Additionally, graphs of

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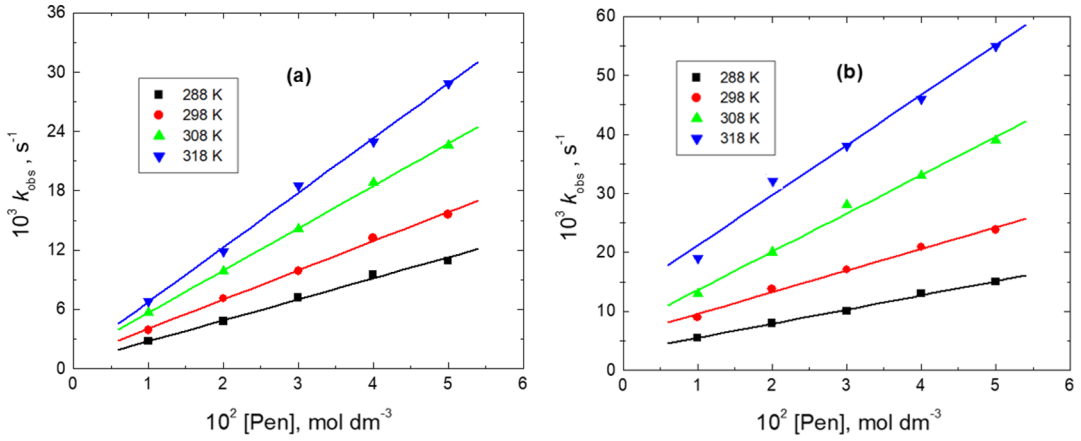

Figure 2. Impact of [Pen] on the values of k_{obs} in the oxidative degradation of penicillin G by CrO_3 in (a) H_2SO_4 and (b) $HClO_4$ media. $[Cr^{VI}] = 5.0 \times 10^{-4}$, $[H^+] = 1.0$, and $I = 2.0$ mol dm^{-3} at various temperatures.

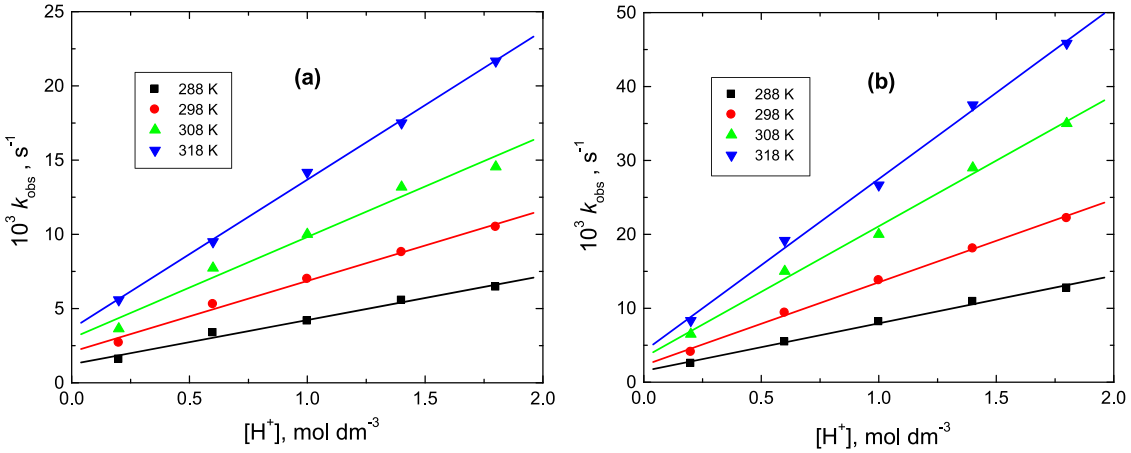

Figure 3. Impact of $[H^+]$ on the values of k_{obs} in the oxidative degradation of penicillin G by CrO_3 in: (a) H_2SO_4 and (b) $HClO_4$ media. $[Cr^{VI}] = 5.0 \times 10^{-4}$, [Pen] = 2.0×10^{-2}, and $I = 2.0$ mol dm^{-3} at various temperatures.

log k_{obs} versus log $[H^+]$ were linear with slopes of 0.87−0.61, as presented in Figure S4.

Impacts of Ionic Strengths and Dielectric Constants of the Reaction Media. To explore the character of the species reacted in the rate-limiting stage of the reactions, the impact of ionic strength on the oxidation rates was studied. This can be achieved by variation of ionic strengths of the reactions media via addition of known concentrations of Na_2SO_4 and $NaClO_4$ as well-known inert electrolytes in sulfuric and perchloric acid solutions, respectively, at firm concentrations of other reaction ingredients. The results showed that the oxidation rates remain considerably unchanged in both cases suggesting that either the substrate or oxidant is uncharged.

Also, the impact of dielectric constants was investigated by altering the acetic acid−water composition in the reaction mixtures with all other circumstances preserved. The rate constants increased insignificantly with lowering the dielectric constants of the reaction media.

Impact of $[Mn^{2+}]$ on the Degradation Rates. For examination of the interference of Cr^{IV} as one of the anticipated intermediates throughout the progress of oxidation reactions, several concentrations of manganese(II) ions were supplemented to the reaction mixtures and their impact on the rates was recorded. The investigational results indicated that the oxidation rates decreased with the increase of $[Mn^{II}]$ as shown in Figure 4.

Impact of Initially Added Cr^{III}. The consequence of initially supplemented chromium(III) ions as a predicted reduction product of chromium(VI) ion on the rates of the

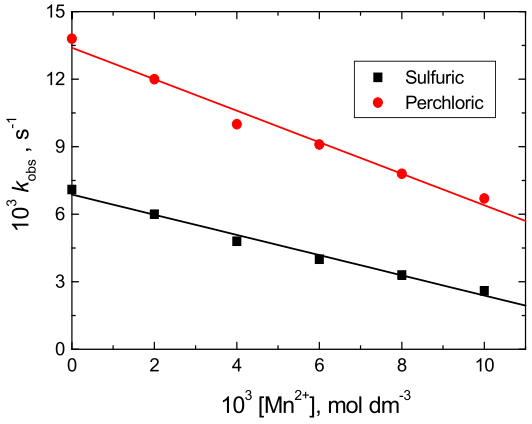

Figure 4. Impact of $[Mn^{2+}]$ on the values of k_{obs} in the oxidative degradation of penicillin G by CrO_3 in H_2SO_4 and $HClO_4$ media. $[Cr^{VI}] = 5.0 \times 10^{-4}$, [Pen] = 2.0×10^{-2}, $[H^+] = 1.0$, and $I = 2.0$ mol dm^{-3} at 298 K.

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existing redox reactions was examined at several [Cr^{III}] values at other constituents constant at 298 K. The results manifested that the initial addition of Cr^{III} did not change significantly the degradation rates in both sulfuric and perchloric acid media.

Impact of Some Divalent Transition Metal Ions on the Degradation Rates. To examine the ability of penicillin G to coordinate with transition metal ions and its impact on its oxidation, the rate of the oxidation reaction that occurred in sulfuric acid solution (as a representative example) was recorded in the presence of variety of [Ni^{2+}], [Cu^{2+}], and [Zn^{2+}] in the range of 2.0−10.0 × 10^{-3} mol dm^{-3} with other constituents constant. The acquired outcomes showed that the degradation rate augmented with enhancing the concentration of the supplemented metal ions as illustrated in Figure 5.

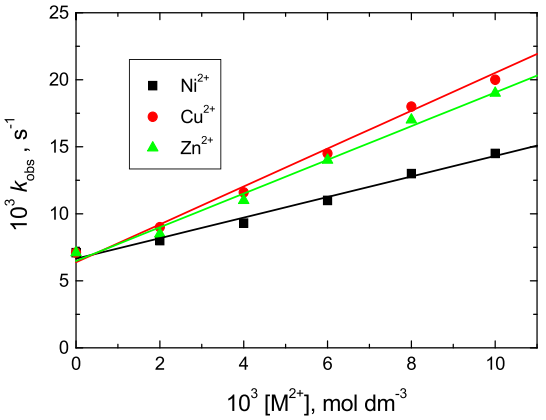

Figure 5. Impact of some divalent transition metal ions on the value of k_{obs} in the oxidative degradation of penicillin G by CrO_3 in the H_2SO_4 medium. [Cr^{VI}] = 5.0 × 10^{-4}, [Pen] = 2.0 × 10^{-2}, [H^+] = 1.0, and I = 2.0 mol dm^{-3} at 298 K.

Impact of Temperature on the Degradation Rates. The oxidative degradation tests were performed at a variety of temperatures, namely, 288, 298, 308, and 318 K at different concentrations of the penicillin G substrate and acidic media in both sulfuric and perchloric acid solutions while at constant [Cr^{VI}] = 5.0 × 10^{-4} and I = 2.0 mol dm^{-3}. The experimental outcomes revealed that the rising temperature increased the oxidation rates. The activation parameters of the rate constant of the slow steps (k_1) and thermodynamic parameters of the equilibrium constants (K_1 and K_2) that appeared in the reaction mechanism were calculated and are tabulated in Tables 2 and 3.

Polymerization Test. The probable interference of free radicals throughout degradation reactions were explored by adding acrylonitrile to the reaction mixtures in both acidic media in inert conditions for approximately 2 h. No white precipitates were produced, signifying the absence of free radical interference in these reactions.

DISCUSSION

It was stated that oxidation reactions using Cr^{VI} as an oxidizer executes through either a one-electron[44] or two-electron[28,29] transfer with interferences of either Cr^{V} or Cr^{IV} intermediates, respectively. In this study, the negative results of the polymerization tests excluded the interference of the Cr^{V} intermediate. On the other hand, participation of Cr^{IV} throughout the chromium(VI) oxidation reactions was supported by the decrease of the oxidation rates upon adding Mn^{2+} ions to the reaction media. This is owing to the capability of Mn^{2+} to trap the Cr^{IV} intermediate if it is present in the reaction medium resulting in a reduction in the oxidation rate.[45] In the existing work, chromium trioxide, as one of the significant chromium(VI) compounds, was employed, which is regarded as a potent oxidizer for several organic substrates.[21−24] It is hydrolyzed in water to form chromic acid according to the following equilibrium[20,46]

$$CrO_3 + H_2O \rightleftharpoons H_2CrO_4 \quad (2)$$

The penicillin G antibiotic (Pen) was anticipated[47] to protonate in acidic media as represented by the equilibrium

$$Pen + H^+ \overset{K_1}{\rightleftharpoons} Pen^+ \quad (3)$$

This suggestion is in good consistency with the present investigation where the acquired less-than unity orders of the reactions with regard to [H^+] can be considered as a proof of penicillin G protonation. Therefore, the protonated penicillin G can be regarded as a more reactive species playing the principal function in the reactions' kinetics.

The present reactions among penicillin G and chromium(VI) oxide in both sulfuric and perchloric acid media exhibited a stoichiometry of 3 Pen:2 Cr^{VI} with a first-order reliance on [Cr^{VI}] and less-than unity orders with regard to [Pen]. The less-than unity orders' reliance on the Pen concentration may be attributed to a complex formation before the slow (rate-limiting) stage of the mechanism. The complex formation was also supported kinetically by the acquired non-zero intercepts of $1/k_{obs}$ versus 1/[Pen] graphs[48] as shown in Figure 6. Additionally, augmenting the degradation rates upon adding Ni^{2+}, Cu^{2+}, or Zn^{2+} can be discussed in the light of complexation between penicillin G and transition-metal ions in acidic media as stated earlier.[42]

In view of the aforementioned arguments, the supreme conceivable oxidation mechanism implicates a rapid complexation among the protonated penicillin G and H_2CrO_4 to construct an intermediate (C) as depicted by the following equation

$$Pen^+ + H_2CrO_4 \overset{K_2}{\rightleftharpoons} [Pen - H_2CrO_4]^+(C) \quad (4)$$

Equilibrium is also approved by the obtained insignificant impacts of variation of both ionic strengths and dielectric constants of the reaction media, which are in agreement with the reactions occurring among an ion with a neutral molecule,[49,50] i.e., among Pen^+ and H_2CrO_4. This intermediate decays in the rate-limiting stage to give the penicillin G intermediate as the primary oxidation product as well as the chromium(IV) intermediate species,

$$[Pen - H_2CrO_4]^+ \xrightarrow[\text{slow}]{k_1} \text{Penicillin intermediate oxidation product} + HCr^{IV}O_3^- \quad (5)$$

The formed penicillin intermediate was rapidly hydrolyzed resulting in the formation of the first final oxidation products of penicillin G (phenyl acetic acid, 2-formyl-5,5-dimethyl-thiazolidine-4-carboxlate ion, ammonium ion, and carbon dioxide) as illustrated in the following equation

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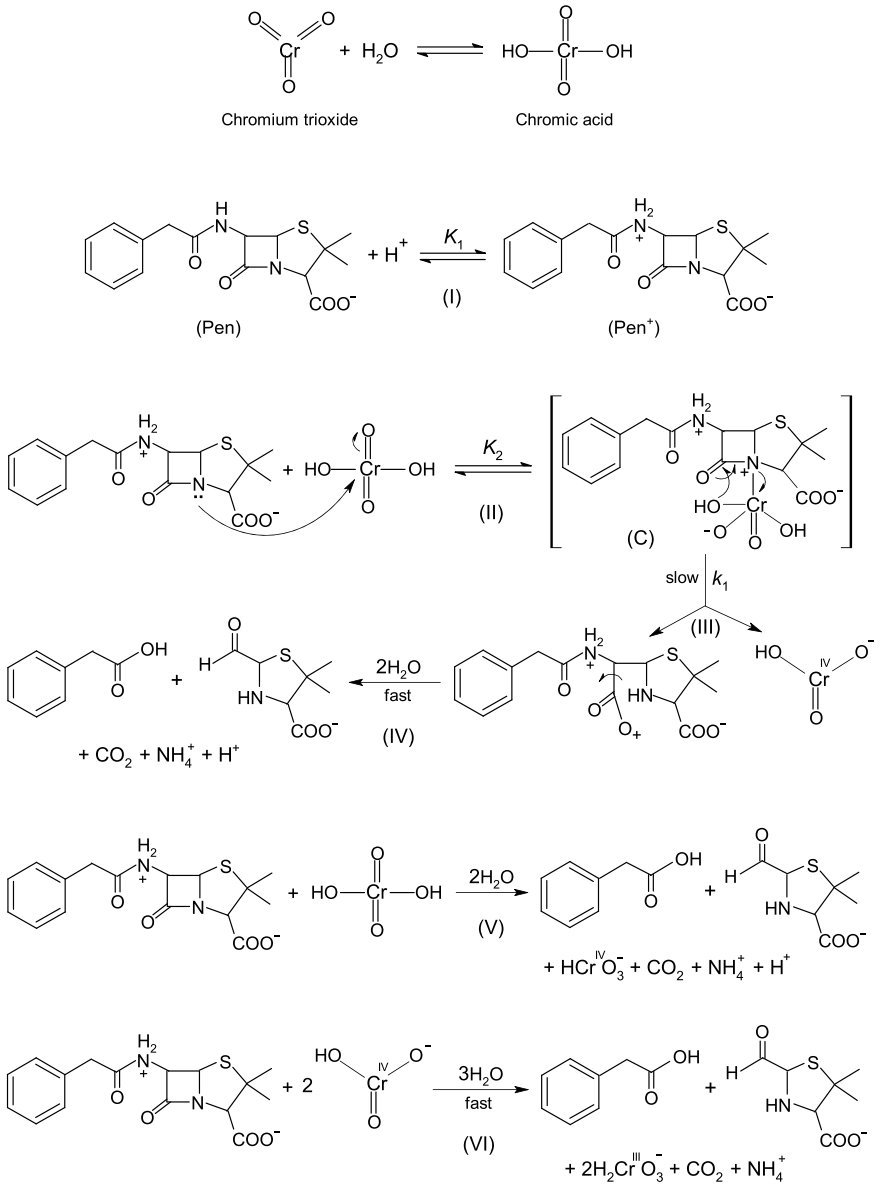
Scheme 1. Mechanism of CrO_3 Oxidative Degradation of Penicillin G in Acidic Media



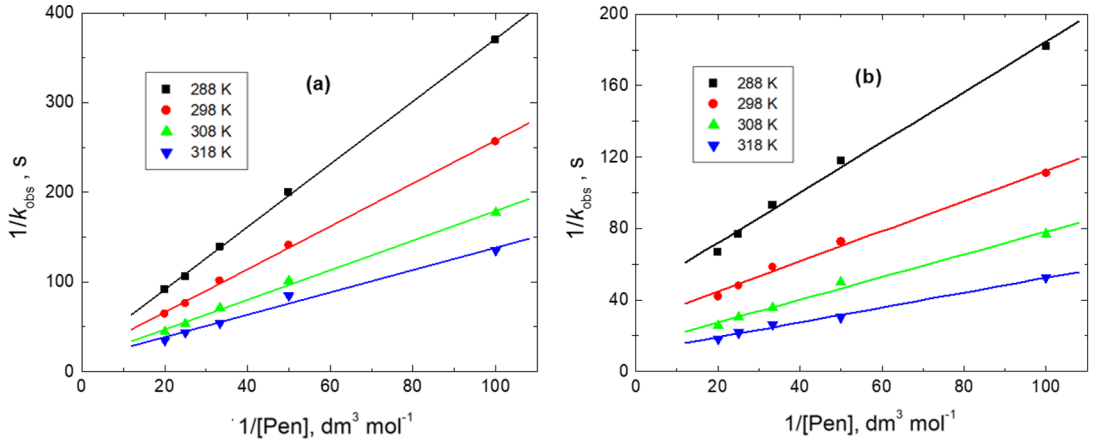


Figure 6. Graphs of $1/k_{obs}$ vs $1/[Pen]$ in the oxidative degradation of penicillin G by CrO_3 in (a) H_2SO_4 and (b) $HClO_4$ media. $[Cr^{VI}] = 5.0 \times 10^{-4}$, $[H^+] = 1.0$, and $I = 2.0$ mol dm^{-3} at various temperatures.

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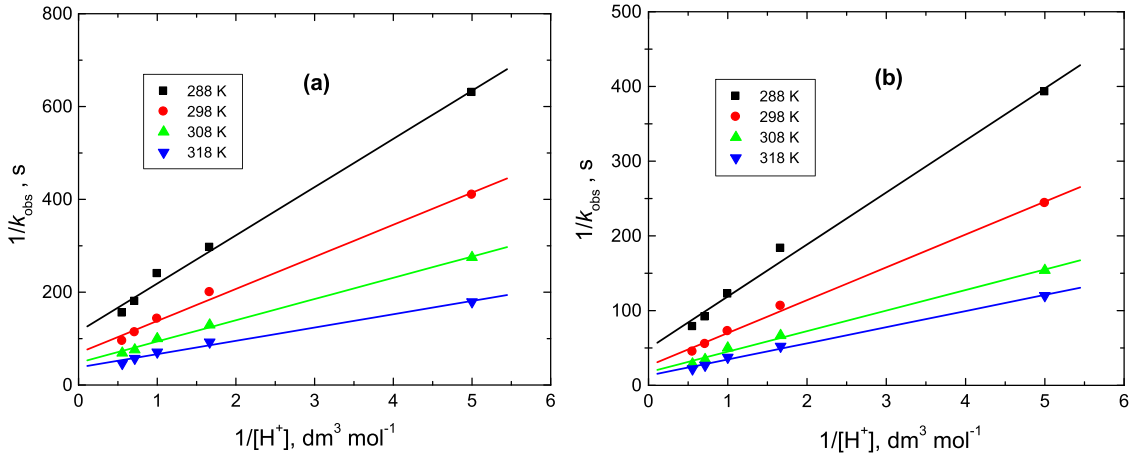

Figure 7. Graphs of $1/k_{obs}$ vs $1/[H^+]$ in the oxidative degradation of penicillin G by CrO_3 in (a) H_2SO_4 and (b) $HClO_4$ media. $[Cr^{VI}] = 5.0 \times 10^{-4}$, $[Pen] = 2.0 \times 10^{-2}$, and $I = 2.0$ mol dm^{-3} at various temperatures.

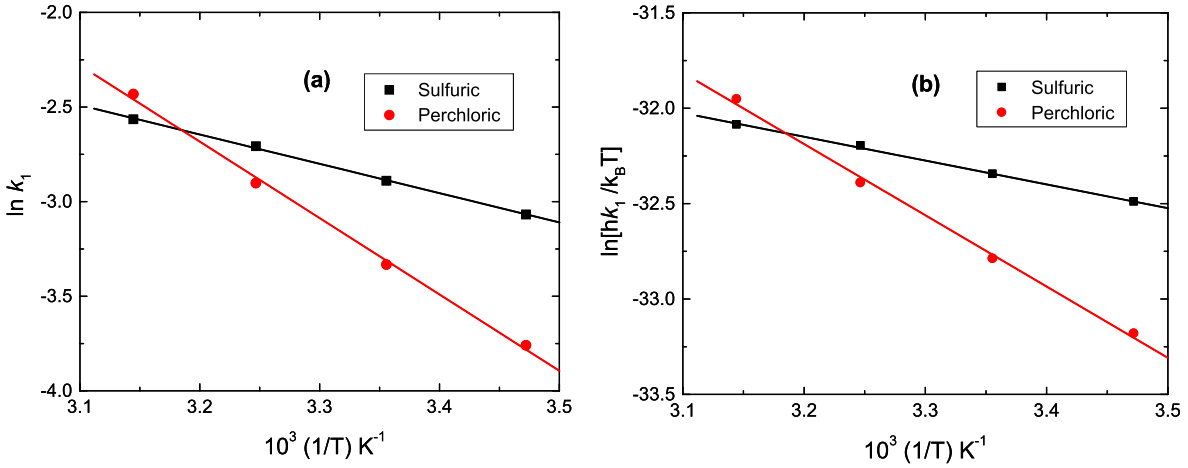

Figure 8. (a) Arrhenius and (b) Eyring graphs of k_1 (s^{-1}) in the oxidative degradation of penicillin G by CrO_3 in H_2SO_4 and $HClO_4$ media. $[Pen] = 6.0 \times 10^{-3}$, $[Cr^{VI}] = 5.0 \times 10^{-4}$, $[H^+] = 1.0$, and $I = 2.0$ mol dm^{-3}.

$$\text{Penicillin intermediate} + 2H_2O \xrightarrow{\text{fast}} \text{First final oxidation products of penicillin} + HCr^{IV}O_3^- \quad (6)$$

Then, another penicillin molecule was further oxidized by additional H_2CrO_4 to produce the second final oxidation products of penicillin and Cr^{IV} species. Finally, the formed two Cr^{IV} reactive intermediate species rapidly attacked the third penicillin molecule to yield the last final oxidation products of penicillin as well as chromium(III) intermediate species as the final reduction product of chromium(VI).[33] The anticipated oxidation mechanism is illustrated in Scheme 1.

The anticipated mechanism (Scheme 1) directs us to the next rate law (see the Appendix)

$$\text{Rate} = \frac{k_1K_1K_2[Cr^{VI}][Pen][H^+]}{1 + K_1[H^+] + K_1K_2[Pen][H^+]} \quad (7)$$

In pseudo-first order circumstances

$$\text{Rate} = \frac{-d[Cr^{VI}]}{dt} = k_{obs}[Cr^{VI}] \quad (8)$$

Comparison of eqs 7 and 8 yields

$$k_{obs} = \frac{k_1K_1K_2[Pen][H^+]}{1 + K_1[H^+] + K_1K_2[Pen][H^+]} \quad (9)$$

With rearranging eq 9, the two principal equations, eqs 10 and 11, are acquired

$$\frac{1}{k_{obs}} = \left(\frac{1 + K_1[H^+]}{k_1K_1K_2[H^+]}\right)\frac{1}{[Pen]} + \frac{1}{k_1} \quad (10)$$

$$\frac{1}{k_{obs}} = \left(\frac{1}{k_1K_1K_2[Pen]}\right)\frac{1}{[H^+]} + \frac{1}{k_1K_2[Pen]} + \frac{1}{k_1} \quad (11)$$

The last acquired equations, eqs 10 and 11, with the prerequisite that the graphs of $1/k_{obs}$ vs $1/[Pen]$ at firm $[H^+]$ and $1/k_{obs}$ vs $1/[H^+]$ at firm $[Pen]$ gave good straight lines were investigationally acquired in both acidic media, emphasizing the validity of the anticipated mechanism and the derived rate laws as presented in Figures 6a,b and 7a,b, respectively. Values of k_1, K_1, and K_2 at four temperatures were estimated from the slopes and intercepts of such graphs and are tabulated in Tables 2 and 3, respectively. The activation parameters of k_1 were estimated from Arrhenius and Eyring graphs (Figure 8a,b, correspondingly) and are listed in Table 2. Additionally, van't Hoff graphs were plotted for varying K_1 and K_2 with

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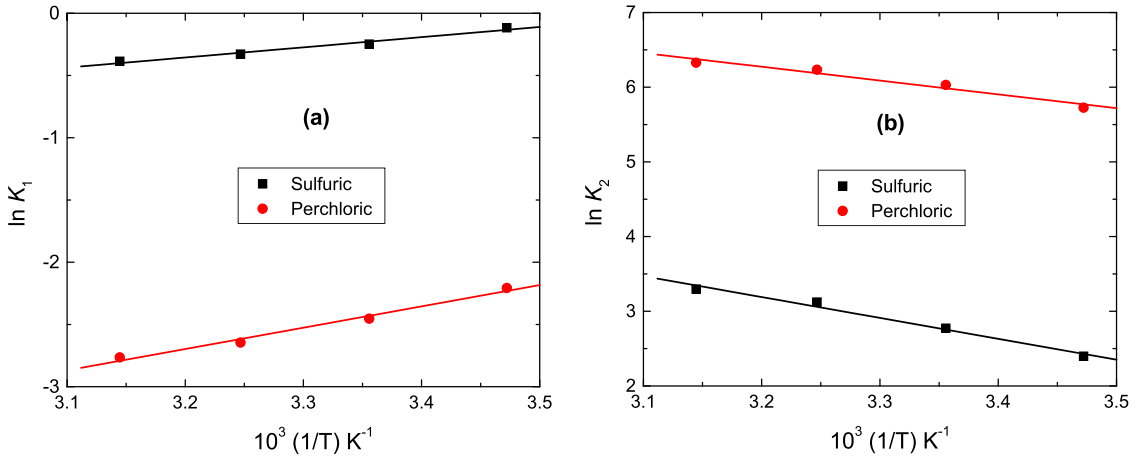

Figure 9. Van't Hoff graphs of the equilibrium constants: (a) K_1 and (b) K_2 in the oxidative degradation of penicillin G by CrO_3 in H_2SO_4 and $HClO_4$ media. [Pen] = 2.0×10^{-2}, [Cr^{VI}] = 5.0×10^{-4}, [H^+] = 1.0, and I = 2.0 mol dm^{-3}.

Table 2. Values of k_1 (s^{-1}) at Various Temperatures and Its Related Activation Parameters in the Oxidative Degradation of Penicillin G by CrO_3 in H_2SO_4 and $HClO_4$ Media[a]

	temperature (K)				activation parameters			
acidic medium	288	298	308	318	$\Delta S^{\neq}$ (J mol^{-1} K^{-1})	$\Delta H^{\neq}$ (kJ mol^{-1})	$\Delta G_{298}{}^{\neq}$ (kJ mol^{-1})	$E_a{}^{\neq}$ (kJ mol^{-1})
sulfuric	4.65	5.56	6.67	7.69	−232.81	10.13	79.51	12.88
perchloric	2.33	3.57	5.49	8.79	−166.28	31.01	80.56	33.51

[a]Experimental error ± 4%.

Table 3. Values of K_1 and K_2 at Various Temperatures and Their Thermodynamic Quantities in the Oxidative Degradation of Penicillin G by CrO_3 in H_2SO_4 and $HClO_4$ Media[a]

		temperature (K)				thermodynamic parameters		
acidic medium	equilibrium constant (dm^3 mol^{-1})	288	298	308	318	ΔH° (kJ mol^{-1})	$\Delta G_{298}{}^{\circ}$ (kJ mol^{-1})	ΔS° (J mol^{-1} K^{-1})
sulfuric	K_1	0.89	0.78	0.72	0.68	−6.78	0.62	−24.83
perchloric		0.11	0.086	0.071	0.063	−14.24	6.07	−68.15
sulfuric	10^{-2} K_2	0.11	0.16	0.227	0.27	23.28	−6.86	101.17
perchloric		3.07	4.16	5.10	5.60	15.38	−14.94	101.74

[a]Experimental error ± 3%.

temperature as presented in Figure 9a,b, respectively. The values of enthalpy, entropy, and free energy of the reactions were estimated and are listed in Table 3.

The acquired moderate activation parameters were found to support the anticipated mechanism and the corresponding rate-law expression. The obtained positive values of free energy of activation, $\Delta G^{\ddagger}$, and enthalpy of activation, $\Delta H^{\ddagger}$, showed that the formed intermediate complexes were solvated and their formation was non-spontaneous and endothermic, respectively. The high negative values of entropy of activation, $\Delta S^{\ddagger}$, anticipated the formation of fixed associative intermediate complexes.[51,52] Moreover, the great activation energy, $E_a{}^{\ddagger}$, showed that the slow stage was the decomposition of formed complexes to form the reaction products.

CONCLUSIONS

The oxidative degradation of the penicillin G antibiotic using chromium trioxide as a potent oxidizer was studied in both sulfuric and perchloric acid solutions. In both acidic media, the oxidative degradation of penicillin G was found to be acid catalysis. Addition of low concentrations of Ni^{2+}, Cu^{2+} or Zn^{2+} ions enhances the oxidation rates. Under comparable investigational circumstances, the oxidation rates in $HClO_4$ are approximately 2-fold greater than in H_2SO_4 media. The oxidation products of penicillin G were described as phenyl acetic acid, 2-formyl-5,5-dimethyl-thiazolidine-4-carboxlate ion, ammonium ion, and carbon dioxide. The activation and thermodynamic parameters were estimated and debated. A believable oxidation mechanism consistent with the product, mechanistic, and kinetic outcomes has been anticipated. This study offers an unprecedented simple and low-cost treatment method for removal or degradation of certain pollutants for protecting the environment and human health.

EXPERIMENTAL SECTION

Materials. All employed chemicals were supplied by Merck or Sigma-Aldrich. Bi-distilled water was used to prepare all solutions in all investigations. Penicillin G sodium salt (98%) was supplied by Sigma, and its solution was prepared by dissolving a conceivable weight of it in bi-distilled water. Chromium trioxide solution was freshly prepared with bi-distilled water, and it was normalized via spectrophotometry. Na_2SO_4 and $NaClO_4$ were used to stabilize the ionic strengths (I) in sulfuric and perchloric acid solutions, respectively. Sulfate salts of Ni^{2+}, Cu^{2+}, and Zn^{2+} ions were from E. Merk, Germany.

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Kinetic Measurements. Kinetic measurements were determined under isolation circumstances where the concentration of penicillin G was in excess with regard to the chromium trioxide oxidant. The absorbance readings were made by transferring the reaction mixture (contained in a 10 mL measuring flask) to a quartz cell with a path length of 1 cm in a temperature-controlled Shimadzu UV−vis−NIR-3600 double-beam spectrophotometer. The reaction kinetics was followed by recording the reduction in Cr^{VI} absorbance as a function of time (reaction times were generally from approximately 700 to 1600 min) at λ = 348 nm, its absorption maximum. First-order graphs of ln Abs. versus time were set to be good straight lines, and the values of the observed pseudo-first-order rate constant (k_{obs}) were estimated as the slopes of these graphs. The listed k_{obs} values (Table 1) were the averages of three independent runs, which were reproducible by up to 3−5%. The orders of the reactions with regard to the reactants were acquired from the gradients of log k_{obs} versus log concn plots for the penicillin substrate and acids, whereas other constituents were kept constant.

APPENDIX

Derivation of the Rate-Law Expression

According to the anticipated mechanism (Scheme 1)

$$K_1 = \frac{[Pen^+]}{[Pen][H^+]},\ [Pen^+] = K_1[Pen][H^+] \quad (A1)$$

and

$$K_2 = \frac{[C]}{[Pen^+][Cr^{VI}]} \quad (A2)$$

From eqs A1 and A2

$$[C] = K_2[Pen^+][Cr^{VI}] = K_1K_2[Pen][Cr^{VI}][H^+] \quad (A3)$$

Stage (III) in Scheme 1 leads to

$$\text{Rate} = \frac{-d[Cr^{VI}]}{dt} = k_1[C] \quad (A4)$$

Substituting eq A3 into eq A4 gives

$$\text{Rate} = k_1K_1K_2[Pen][Cr^{VI}][H^+] \quad (A5)$$

The total concentration of penicillin G, $[Pen]_T$,

$$[Pen]_T = [Pen]_F + [Pen^+] + [C] \quad (A6)$$

where "T" and "F" mean total and free.

Substitution of eq A1 into eq A6 yields

$$[Pen]_T = [Pen]_F + K_1[Pen][H^+] + K_1K_2[Pen][Cr^{VI}][H^+] \quad (A7)$$

$$[Pen]_T = [Pen]_F(1 + K_1[H^+] + K_1K_2[Cr^{VI}][H^+]) \quad (A8)$$

Thus

$$[Pen]_F = \frac{[Pen]_T}{1 + K_1[H^+] + K_1K_2[Cr^{VI}][H^+]} \quad (A9)$$

Owing to the used low concentration of Cr^{VI}, the term $K_1K_2[Cr^{VI}][H^+]$ in the denominator can be neglected. Hence

$$[Pen]_F = \frac{[Pen]_T}{1 + K_1[H^+]} \quad (A10)$$

Also, $[Cr^{VI}]_T$ is given by

$$[Cr^{VI}]_T = [Cr^{VI}]_F + [C] = [Cr^{VI}]_F + K_1K_2[Pen][Cr^{VI}][H^+] \quad (A11)$$

$$[Cr^{VI}]_T = [Cr^{VI}]_F(1 + K_1K_2[Pen][H^+]) \quad (A12)$$

Subsequently

$$[Cr^{VI}]_F = \frac{[Cr^{VI}]_T}{1 + K_1K_2[Pen][H^+]} \quad (A13)$$

The high concentration of $[H^+]$ employed in the existing study leads us to suggest that

$$[H^+]_F = [H^+]_T \quad (A14)$$

Substituting eqs A10, A13, and A14 into eq A6 (and omitting "T" and "F" subscripts) gives

$$\text{Rate} = \frac{k_1K_1K_2[Cr^{VI}][Pen][H^+]}{1 + K_1[H^+] + K_1K_2[Pen][H^+]} \quad (A15)$$

In the pseudo-first-order conditions, the rate law with regard to $[Cr^{VI}]$ can be expressed as follows

$$\text{Rate} = \frac{-d[Cr^{VI}]}{dt} = k_{obs}[Cr^{VI}] \quad (A16)$$

Comparison of eqs A15 and A16 leads to

$$k_{obs} = \frac{k_1K_1K_2[Pen][H^+]}{1 + K_1[H^+] + K_1K_2[Pen][H^+]} \quad (A17)$$

Rearranging eq A17 results in

$$\frac{1}{k_{obs}} = \left(\frac{1 + K_1[H^+]}{k_1K_1K_2[H^+]}\right)\frac{1}{[Pen]} + \frac{1}{k_1} \quad (A18)$$

$$\frac{1}{k_{obs}} = \left(\frac{1}{k_1K_1K_2[Pen]}\right)\frac{1}{[H^+]} + \frac{1}{k_1K_2[Pen]} + \frac{1}{k_1} \quad (A19)$$

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.0c05288.

FT-IR spectra of penicillin G and its oxidation products; graphs of ln Abs. vs time; graphs of log k_{obs} vs antibiotic concentration; and plots of log k_{obs} vs $[H^+]$ (PDF)

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Notes

The authors declare no competing financial interest.

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