Research Article

Oxidation of Syringaldehyde by Alkaline Hexacyanoferrate(III) – A Kinetic and Mechanistic Study

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Abstract

The kinetics of oxidation of syringaldehyde by hexacyanoferrate(III) in aqueous alkaline medium was studied. The first order dependence on concentration of hexacyanoferrate (III) and fractional order dependence on both syringaldehyde and alkali is supported by the derived rate law. A retarding effect was observed by one of the products hexacyanoferrate(II). Increasing ionic strength and dielectric constant of the medium increased the rate of the reaction. The effect of temperature on the rate of reaction has also been studied and activation parameters have been evaluated. A mechanism based on the experimental results is proposed and the rate law is derived.

Keywords: Oxidation; syringaldehyde; Kinetics; 4-hydroxy-3,5-dimethoxybenzaldehyde, Potassium ferricyanide.

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Introduction

4-hydroxy-3,5-dimethoxybenzaldehyde otherwise known as syringaldehyde is a plant phenol which can be made from the decomposition of lignin [1]. Syringaldehyde is also formed in oak barrels and extracted into whisky, which it gives spicy, smoky, hot and smoldering wood aromas [2]. Its use as a pharmaceutical intermediate comes from recent patents. One of the patents describes the use of syringaldehyde as an intermediate to produce a drug to treat breast cancer [3], obesity [4], its anti hyperglycemic effect [5] and insecticidal properties [6] astonish its pharmaceutical and commercial value. Other patents mention its use as an enhancer for enzymatic dyeing of keratin fibers and enzymatic bleaching [7-10]. Syringaldehyde is also used as an antioxidant [11], anticancer and anti-inflammatory medicinal spice suggesting that additional commercial applications exist for the compound [12]. The role of syringaldehyde as an antifungal agent against the medicinally important yeast *Candida guilliermondii* seems to be promising. It was reported that syringaldehyde successfully inhibited the *C. guilliermondii* growth rate and reduced xylitol production effectively.

The fungicidal effect is most likely due to the aldehyde moiety. The hydroxyl substituent in syringaldehyde is suspected to play a key role in enhancing this fungicidal effect [13]. Syringaldehyde is widely used as a molecular marker to monitor pollution sources and detect the extent of combustion [14]. It also helps in the analysis of amino acids [15] and as a chromo-phoric reagent to measure "free" chlorine levels in water samples [16]. Some species of insects use syringaldehyde in their chemical communication systems. *Scolytus multistriatus* uses it as a signal to find a host tree during oviposition [17].

The present work reports the kinetics of oxidation of syringaldehyde by hexacyanoferrate(III) in alkaline medium and evaluates the reaction constants. Mechanistic aspects are also discussed. The oxidation of reducing sugars [18], phenols and naphthols [19], vanillin [20], enolizable and non-enolizable aldehydes [21] and many other organic compounds by this oxidant in alkaline medium have been studied and reported by many researchers.

Experimental

Materials and Methods

All the chemicals (AR grade) were purchased from SD fine chemicals Ltd., and used without further purification. A solution of hexacyanoferrate(III) was prepared by dissolving $K_3[Fe(CN)_6]$ in double distilled water and standardized iodometrically [22a]. NaOH and KCl were employed to maintain the required alkalinity and ionic strength respectively.

Kinetic Measurements

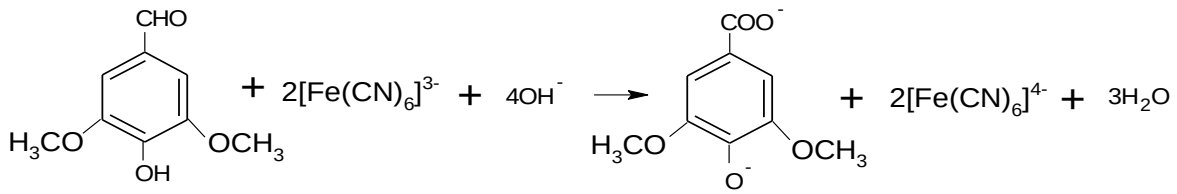
All kinetic measurements were performed under pseudo first-order conditions where [syringaldehyde] was always in excess over hexacyanoferrate(III), at a constant ionic strength in alkaline medium at temperature of (30.0 ± 0.1)˚C. The reaction was initiated by mixing the thermostatted solutions of hexacyanoferrate(III) and syringaldehyde which also contained the required concentration of NaOH and KCl. The progress of the reaction was followed by observing the disappearance of hexacyanoferrate(III) titrimetrically. Pseudo first- order rate constants, k_{obs}, were obtained (**Table 1**) from the slopes of plots of $\log_{10}[Fe(CN)_6^{3-}]$ *versus* time; the plots were linear and the k_{obs} values were reproducible to within ±2%.

Table 1 Effect of Variations of $[Fe(CN)_6^{3-}]$, [Substrate] and $[OH^-]$ on the Oxidation of Syringaldehyde by $Fe(CN)_6^{3-}$ at 30 °C, I = 1.0 mol·dm^{-3}

$[Fe(CN)_6^{3-}] \times 10^3$ (mol.dm^{-3})	[Syringaldehyde] × 10^2 (mol. dm^{-3})	$[OH^-]$ (mol. dm^{-3})	$k_{obs} \times 10^4$ (s^{-1})
4.0	5.0	0.3	2.63
5.0	5.0	0.3	2.66
6.0	5.0	0.3	2.65
7.0	5.0	0.3	2.66
8.0	5.0	0.3	2.64
5.0	**4.0**	0.3	2.21
5.0	**5.0**	0.3	2.66
5.0	**6.0**	0.3	3.12
5.0	**7.0**	0.3	3.83
5.0	**8.0**	0.3	4.56
5.0	5.0	**0.1**	1.54
5.0	5.0	**0.2**	2.05
5.0	5.0	**0.3**	2.66
5.0	5.0	**0.4**	3.73

Stoichiometry and Products Aanalysis

Different sets of reaction mixtures containing varying ratios of reactants to $[Fe(CN)_6^{3-}]$ in the presence of constant amount of OH^- and KCl were kept for about 24 hours at 30°C in a closed vessel. The remaining hexacyanoferrate(III) was estimated titrimetrically. The results indicated that two moles of hexacyanoferrate(III) consumed 1 mol of syringaldehyde as given in the following equation.



The stoichiometric ratio suggests that the main reaction products are 3,5-Dimethoxy-4-hydroxybenzoic acid (syringic acid) and $Fe(CN)_6^{4-}$. The product syringic acid is identified by its spot test [23], isolated by acidifying the

reaction mixture followed by ether extraction and confirmed by IR spectrum and its melting point at 203.5°C (Experimental value 205°C). The characteristic IR absorption bands at 1595 cm^{-1}1683 cm^{-1}, 2926 cm^{-1}, confirmed the presence of carboxylic acid group, the IR band at 3365 cm^{-1} confirmed the hydroxyl group and the same at 2852 cm^{-1} confirmed the presence of $–OCH_3$ group. The concentration of the reduction product, $Fe(CN)_6^{4–}$, was estimated [22b] by titrating against a Ce(IV) solution.

Results and Discussion

Effect of [Hexacyanoferrate (III)]

The rates were measured by varying the concentration of hexacyanoferrate(III) in the range of 4.0×10^{-3} to 8.0×10^{-3} $mol.dm^{-3}$, keeping all other reactant concentrations and ionic strength as constant (Table 1). The constancy in the value of rate constants irrespective of the concentration of the hexacyanoferrate(III) confirmed the first order dependence on hexacyanoferrate(III). This was also confirmed from the linearity of plots of $\log_{10}$ [hexacyanoferrate(III)] *versus* time ($r = 0.999$ and $s \leq 0.004$) for up to 80% completion of the reaction.

Effect of [Syringaldehyde]

The concentration of substrate syringaldehyde , was varied for the range of 4.0×10^{-2} to 8.0×10^{-2} $mol.dm^{-3}$ at 30°C keeping all other reactant's concentrations and conditions constant (Table 1). The k_{obs} values increased with increasing concentration of syringaldehyde. A plot of log k_{obs} against log [syringaldehyde] is linear (**Figure1**a). The order was found to be fractional (= 0.8).

Effect of [Alkali]

The dependence of the reaction rate on hydroxide ion has been studied in the range 0.10 to 0.4 $mol.dm^{-3}$ keeping the concentration of substrate and oxidant constant at ionic strength showed the values of the rate constants increased with increasing [OH^-] (Table 1). The order was found to be less than unity (=0.71). A plot of log k_{obs} against log [OH^-] is linear. (Figure 1b)

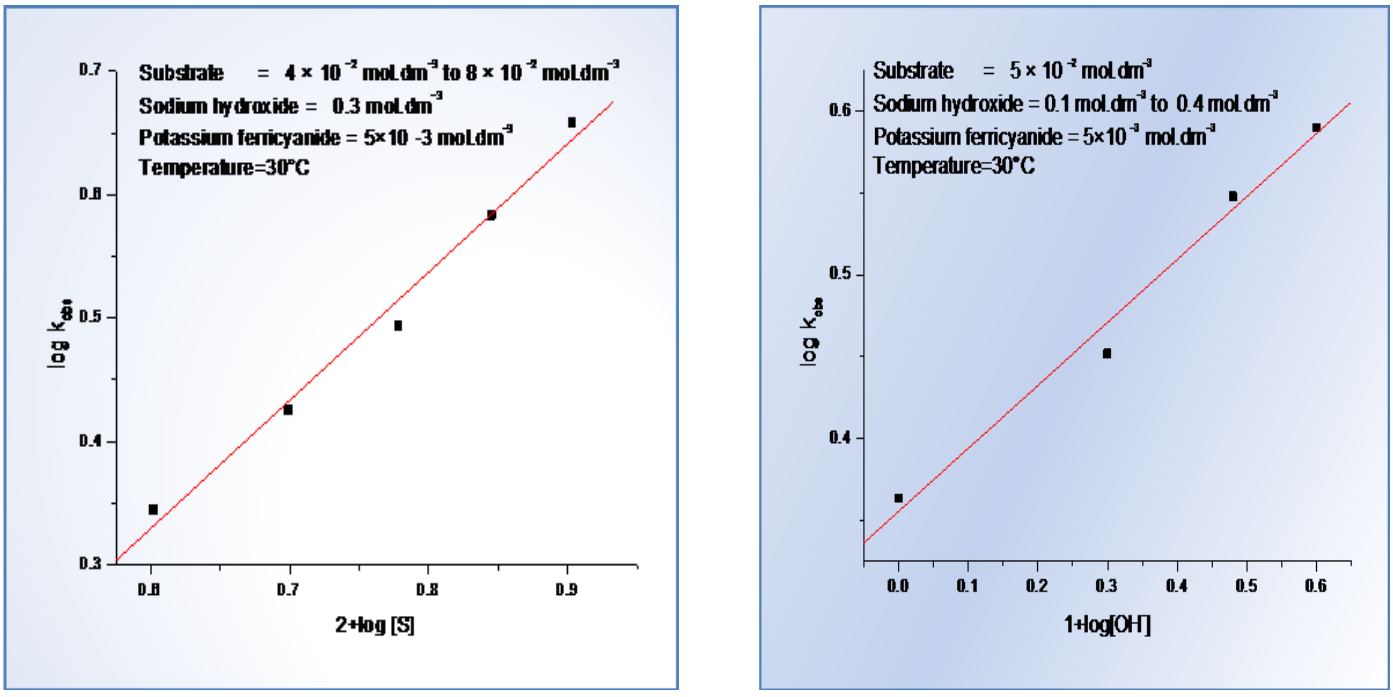


Figure 1 (a) First order plot: 2+ log[Substrate] against log $k_{obs,}$ (b) First order plot: 1+ log[OH^-] against log k_{obs}

Effect of Ionic Strength and Solvent Polarity

The change in the ionic strength was effected by the addition of potassium chloride of known strength. (**Table 2**) It is clear that the rate of reaction is increased by the addition of KCl which confirms reaction between similarly charged species in the rate determining step. As the dielectric constant of the medium is decreased, a decrease in rate of oxidation is observed (Figure 2b).

Effect of Initially Added Product

The effect of initially added product hexacyanoferrate(II) on the rate of reaction was also studied in the range of 1.0×10^{-3} to 4.0×10^{-3} mol.dm^{-3} at 30°C by keeping ionic strength and other concentrations constant (**Table 3**). It has retarding effect on the rate of oxidation, revealing that the step in which hexacyanoferrate(II) is formed as a product must be reversible.

Table 2 Effect of varying Ionic strength on reaction rate

[Substrate]=5×10^{-2} mol.dm^{-3}; [OH$^-$] = 0.3 mol.dm^{-3}; [oxidant] = 5×10^{-3} mol.dm^{-3}.					
I (mol.dm^{-3})	1.00	1.10	1.20	1.30	1.40
$10^4 k$ (s^{-1})	2.65	3.00	3.67	4.36	5.10

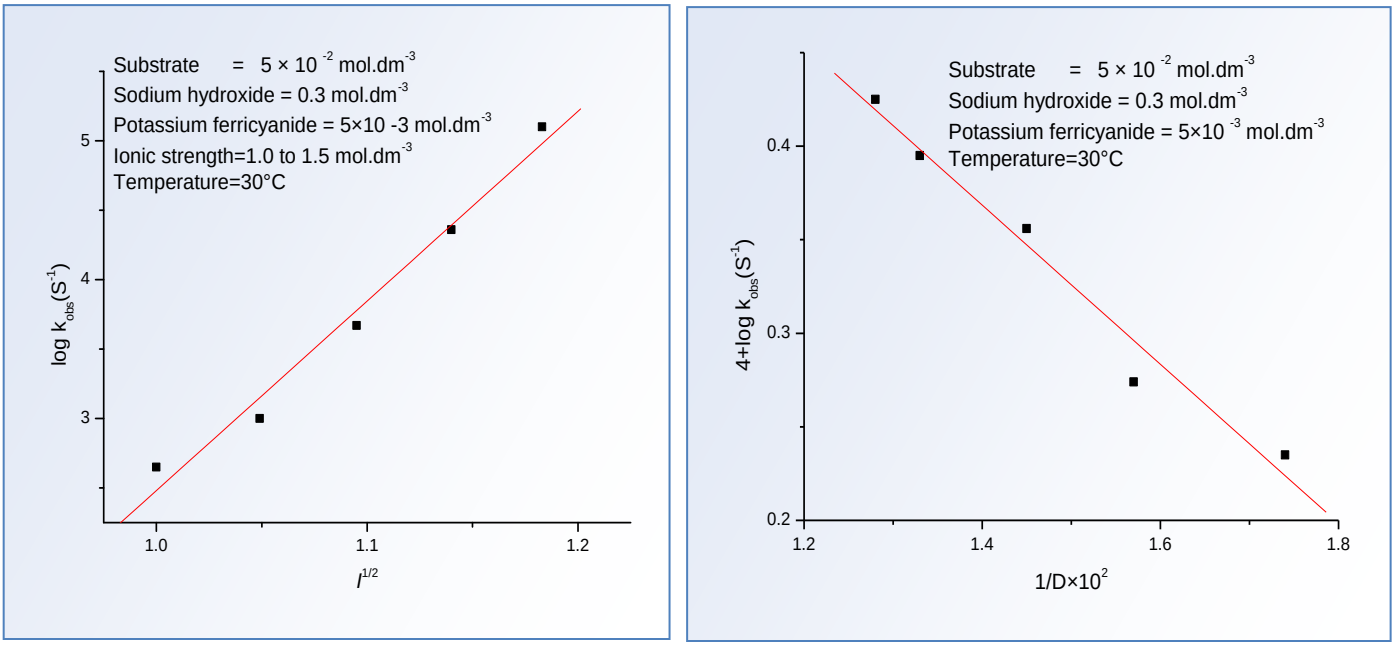


Figure 2 (a) Effect of ionic strength of the medium (b) Effect of dielectric constant on oxidation of syringaldehyde by hexacyanoferrate(III)

Table 3 Effect of Added Product, hexacyanoferrate (II), on the Oxidation of syringaldehyde by Hexacyanoferrate(III) in Aqueous Alkaline Medium

[syringaldehyde] = 5×10^{-2} mol.dm^{-3}; [OH$^-$] = 0.3 mol.dm^{-3}; [Hexacyanoferrate(III)] = 5×10^{-3} mol.dm^{-3}; I = 1.0 mol.dm^{-3}					
$[Fe(CN)_6^{4-}] \times 10^3$	0	1	2	3	4
$k_{obs} \times 10^4$ (s^{-1})	2.66	2.60	2.52	2.49	2.32

Effect of Temperature

The oxidation of syringaldehyde by alkaline hexacyanoferrate (III) was carried out in the temperature range 303-323 K and it was observed that the rate of reaction increased with an increase in temperature (**Table 4**). The activation parameters corresponding to the rate constants were evaluated from the Arrhenius plots of $\log_{10} k_{obs}$ versus 1/T which was linear with r = 0.99. (**Table 5**)

Table 4 Effect of Temperature on the Oxidation of Syringaldehyde by Hexacyanoferrate(III) in Aqueous Alkaline Medium

[syringaldehyde] = 5×10^{-2} mol.dm^{-3}; [OH^-] = 0.3 mol.dm^{-3}; [Hexacyanoferrate(III)] = 5×10^{-3} mol.dm^{-3}; I= 1.0 mol.dm^{-3}					
Temperature (K)	303	308	313	318	323
$k_{obs} \times 10^4$ (s^{-1})	2.66	3.83	5.45	6.76	8.86

Table 5 Activation Parameters for the Oxidation of Syringaldehyde by Hexacyanoferrate(III) in Aqueous Alkaline Medium

E_a(kJ mol^{-1})	**ΔH(kJ mol^{-1})**	**ΔS(J.K^{-1} mol^{-1})**	**ΔG (kJ. mol^{-1})**
48.40	45.90 ±0.1	−101 ± 5	77 ± 3

Test for Free Radicals

The interference of free radicals was tested by adding few drops of methyl acrylate to the mixture of solution of syringaldehyde in NaOH and hexacyanoferrate(III). As there occurred turbidity, interference of free radicals was confirmed.

Mechanism of Reaction

The reaction being first order in [oxidant], fractional order in [syringaldehyde] & [OH^-] and being retarded by the addition of hexacyanoferrate(II) can be accommodated in the following **Scheme 1**. The oxidation was initiated by the formation of the anion of syringaldehyde. The anion can transfer an electron to hexacyanoferrate(III), resulting in the formation of a radical is the slow and rate determining step. The formation of complex occurs primarily before the slow step. The second molecule of hexacyanoferrate(III) abstracts an electron from the radical and subsequently leads to the formation of products. The formation of complex is proven kinetically based on derived rate law by the non-zero intercept (**Figure 3**) of graph of $1/k_{obs}$ *versus* 1/ [Substrate].

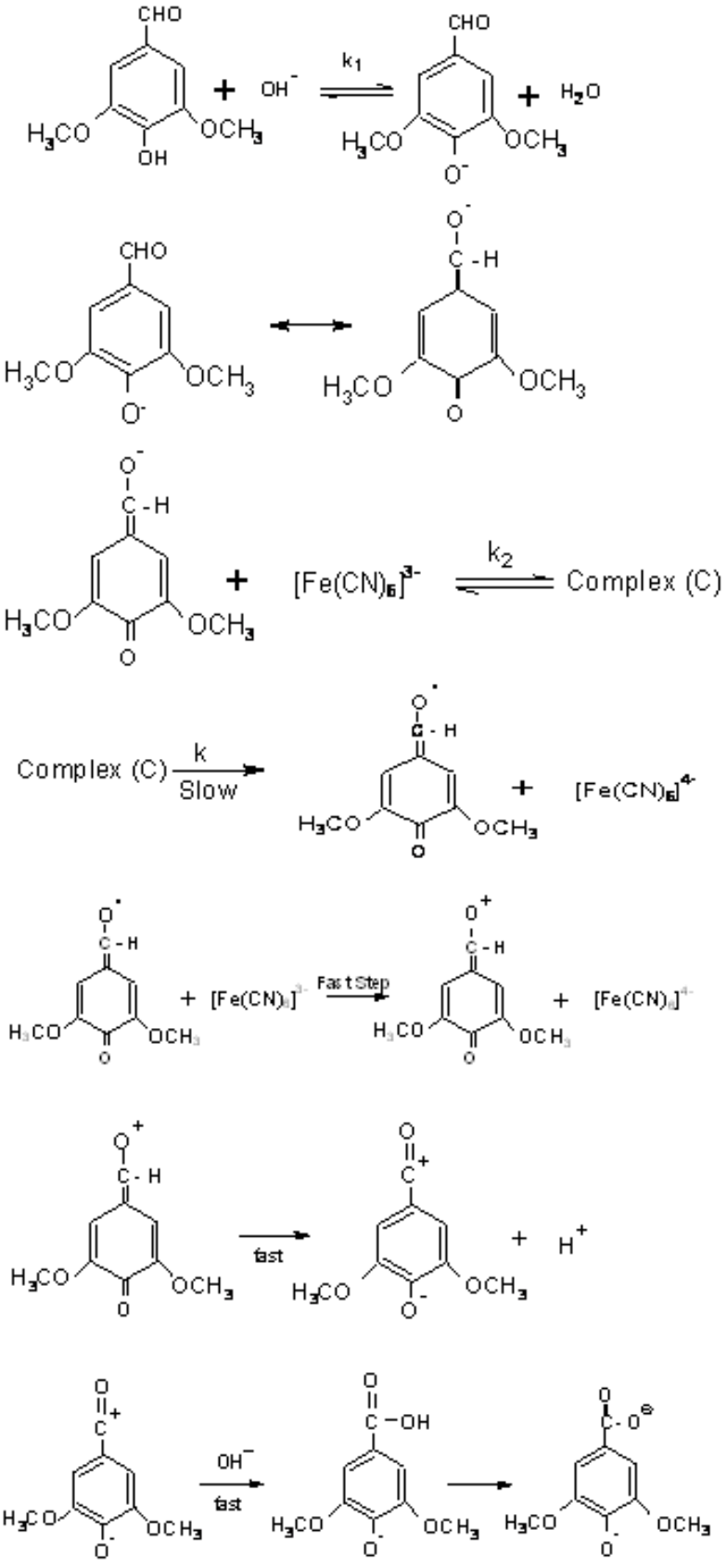
The rate law is given as follows;

$$S + OH^- \underset{}{\overset{k_1}{\rightleftharpoons}} S^- + H_2O$$

$$S^- + [Fe(CN)_6]^{3-} \overset{k_2}{\rightleftharpoons} \text{Complex (C)}$$

$$\text{Complex (C)} \xrightarrow[\text{Slow}]{k} \text{Radical} + [Fe(CN)_6]^{4-}$$

Scheme 1


CHO
OH⁻
k1
H2O
H3CO
OCH3
OH
O⁻
C-H
O
[Fe(CN)6]3-
k2
Complex (C)
k
Slow
[Fe(CN)6]4-
Fast Step
fast
H+
OH⁻
C-OH
C-O⊖

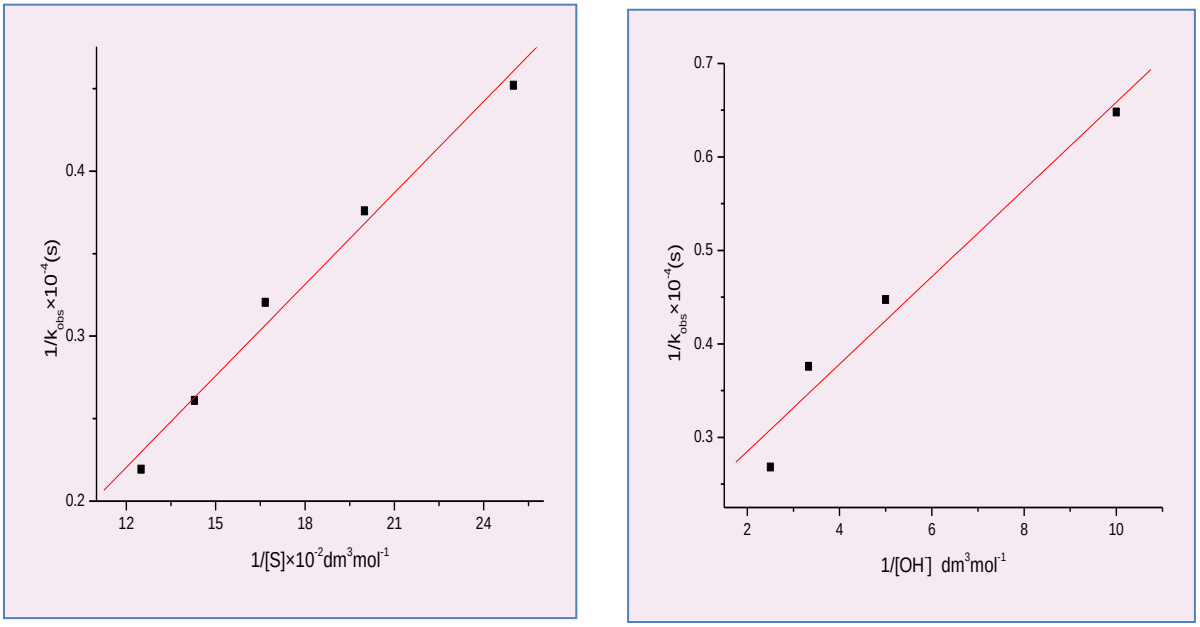
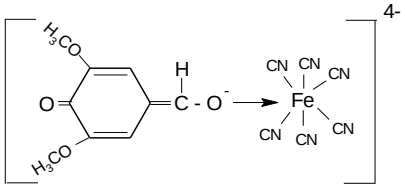


Figure 3 Graph of $1/k_{obs}$ *versus* 1/ [Substrate] and $1/k_{obs}$ *versus* 1/ $[OH^-]$ showing non-zero intercept

The probable structure of the complex is given as:



$$\frac{-dFC}{dt} = k_2[S^-][FC] \quad (1)$$

$$\frac{-dFC}{dt} = \text{Rate} = k[\text{Complex}] \quad (2)$$

Applying steady state approximation for Complex 'C'

$$[\text{Complex}] = \frac{k_2[S^-][FC]}{k\ [\text{Radical}][FC']} \quad (3)$$

Substituting the terms in equation (3) & (2) and simplifying we get,

$$\text{Rate} = \frac{kk_1k_2[S][OH^-][FC]}{(1+k_1[OH^-])(1+k_1k_2[S][OH^-])(1+k_2[FC])} \quad (4)$$

As the concentration of $Fe(CN)_6^{4-}$ used in the study is very low, term $(1+k_2[FC])$ tends to unity. Then equation (4) becomes,

$$\text{Rate} = \frac{kk_1k_2[S][OH^-][FC]}{(1+k_1[OH^-])(1+k_1k_2[S][OH^-])} \quad (5)$$

Note: The abbreviations S, FC & FC' represent syringaldehyde, hexacyanoferrate(III) and hexacyano-ferrate(II) respectively.

Conclusions

The kinetic studies clearly demonstrate that oxidation of syringaldehyde by hexacyanoferrate(III) in alkaline medium is favored by the outer-sphere formation of $Fe(CN)_6^{4-}$and free radicals in slow step which is followed by the rapid

oxidation of free radicals by $Fe(CN)_6^{3-}$ to give products. Even though it involves the retardation by one of the products, the overall mechanistic sequence described here is consistent with product, mechanistic and kinetic studies.

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