A kinetic and mechanistic study on the oxidation of isatin by peroxomonosulphate in acetonitrile medium

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ABSTRACT

Kinetic investigation on the oxidation of isatin in an acidified solution of peroxomonosulphate has been studied in the temperature range of 323-333K. Increase in the concentration of H^+ ion showed first order. The influence of ionic strength and oxidant on the rate was found to be insignificant. The various thermodynamic parameters were calculated form rate measurements at 323, 328 and 333K respectively. A suitable mechanism in conformity with the kinetic observations has been proposed and the rate law was derived on the basis of the observed data. The product isatoic anhydride was confirmed from the IR&NMR spectral analysis.

Keywords: Kinetics, oxidation, peroxomonosulphate, isatin, isatoic anhydride

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INTRODUCTION

Heterocyclic compounds with ring system are of special importance in life processes for example imidazole, indole, pyrimidine and purine. Among these imidazole and indole are present in proteins, pyrimidine and purine are found in genes. Some indole derivatives like indole-3-acetic acid and indole-3-propionic acid have great growth promoting action on plants and are known as heteroauxins or phytoharmones. Isatin was first obtained as a product from the oxidation of indigo by nitric and chromic acids [2]. Methylene oxindoles derived from isatins bearing a benzimidazole ring [3], as well as thioindigoid thiazolidines[4] have also been used for dyeing synthetic and natural fibers.

Peroxomonosulphate is a class of chemical compound which possess a unique property of participating in many chemical reactions with a potential multitude of functional activities as exemplified by variety of applications as oxidants in synthesis, initiators in emulsion polymerisation, bleaching agents, metal cleaning rods, rocket fuel, oxidative starch modifier in water treatment and in several germicidal and biological reactions. The high oxidation potential (1.82V) suggests the feasibility of many room temperature oxidations with peroxomonosulphate [4-12]. The synthetic utility of peroxomonosulphate with different kinds of organic substrate has been reported [13]. Hence the study on the oxidation of isatin by peroxomonosulphate was chosen which was of much biological and chemical significance.

MATERIALS AND METHODS

All the chemicals required were of AR grade E.Merck samples and used as such. Doubly distilled water was employed in the preparation of aqueous solutions. In a typical experiment, appropriate amount of isatin, sulphuric acid, acrylonitrile, sodium bisulphate and water were taken in a reaction vessel and thermostated at the desired

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temperature. The temperature range selected was between 323-333 K.A measured amounts of oxidant peroxomonosulphate also thermostated at the same temperature. A required amount of oxidant was pipetted out into the reaction mixture and the liberated iodine was titrated against thio sulphate using starch as the indicator.

The progress of the reaction was monitored by iodometric determination of unreacted oxidant. The course of the reaction was followed for 75% of completion of the reaction. Plot of log [oxidant] Vs time were made. The values of pseudo first order rate constants k' obtained were reproducible within ±5%.

Product analysis
The reaction mixture containing a slight excess of peroxomonosulphate over the substrate with other additives maintained as in the regular kinetic runs was kept aside at room temperature for about 48 hours for completion of the reaction. Then the remaining reaction mixture was poured into doubly distilled water. A residual solid thus obtained was filtered washed and dried. The solid mass was characterised as a product by FT-IR and ^{1}H NMR spectral data.

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RESULTS

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1. Dependence of reaction on oxidant and substrate
The kinetic run was carried out with stoichiometric excess of substrate at constant peroxomonosulphate. Plots of log [PMS] Vs time were linear with slope equal to unity. The value of pseudo first order rate constant k' is given in Table -1. An increase in [isatin] has increased the pseudo first order rate constant, thus indicating first order dependence on [isatin]. In order to determine the order of reaction with respect to the oxidant the reaction was carried out at different initial concentrations of oxidant and at fixed concentration of other reactants. The k' values are given in Table-2 and it was seen that the reaction was independent of PMS concentration. This clearly shows that the reaction is of first order with respect to the change in concentration of oxidant.The values of k_2 (mol dm^{-3} s^{-1}) were evaluated from the slope of k'(s^{-1}) Vs [isatin] plots (Fig.2). The k_2 (mol dm^{-3} s^{-1}) values thus obtained from such plots (Table-3) were in agreement with the corresponding values calculated from the factor k'(s^{-1})/[isatin].

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Table: 1 Effect of [substrate]

[Substrate] x10^{-2} mol dm^{-3}	k' x 10^{-5}, s^{-1}
2.0	15.51
2.5	19.58
3.0	23.06
3.5	26.79
4.0	30.09

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[PMS] = 2 x 10^{-3} mol dm^{-3},[H$^+$] = 0.02 mol dm^{-3},μ = 0.3 mol dm^{-3},Solvent=40%aqueous acetonitrile (v/v)

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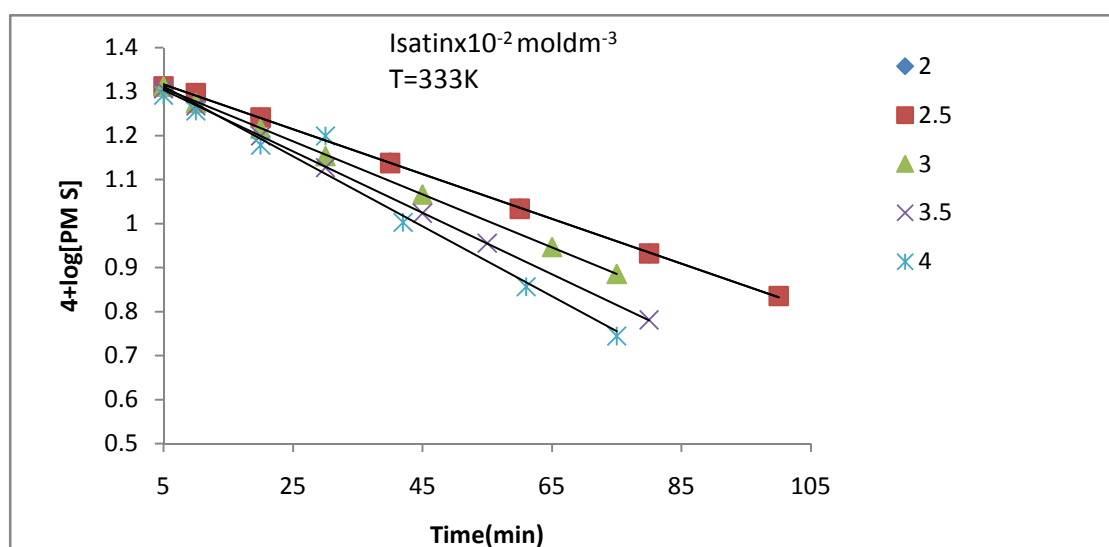
Fig-1 Effect of isatin

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Table: 2 Effect of change in concentration of oxidant on the reaction rate

[PMS] x 10^{-3} mol /dm^3	1.0	1.5	2.0	2.5	3.0
k' x 10^{-5}, s^{-1}	-	23.49	23.03	23.06	23.26

[substrate] = 3 x 10^{-2} mol dm^{-3},[H$^+$] = 0.02 mol dm^{-3},μ = 0.3 mol dm^{-3},Solvent=40%aqueous acetonitrile(v/v)

Table: 3 Evaluation of k$_2$

Temp(K)	k$_2$ x10^3(mol dm^{-3}) Graphical	k$_2$ x10^3(mol dm^{-3}) Observed	R(correlation coefficient)
323	5.16	5.13	0.9995
328	6.58	6.60	0.9995
333	7.57	7.70	0.9992
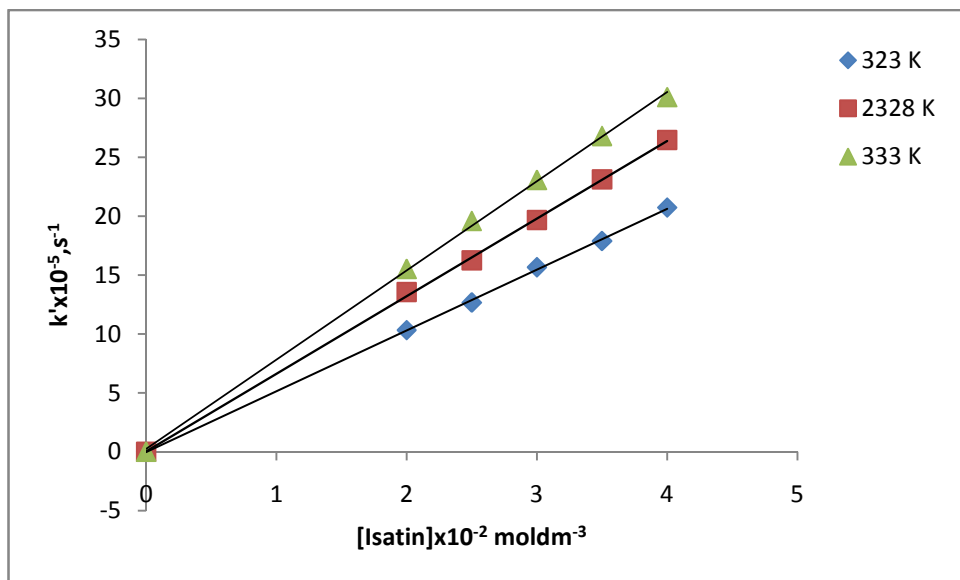
Fig-2 plot of k' Vs [isatin]

2. First order with respect to [H$^+$]

Increase of [H$^+$] was found to increase the reaction rate marginally in the case of isatin(Table -4). This dependence of k' (s^{-1}) on [H$^+$] observed is due to the presence of polar functional group like >C=O in isatin. That is these functional groups exhibit considerable degree of polarity due to the electronegative oxygen atom. Hence, the ability of these groups to get protonated by [H$^+$] being made available from the H$_2$SO$_4$ used in the experiments. It may be noted that the observed [H$^+$] effect in these substrates is not due to any acid-base equilibrium of the oxidant, peroxomonosulphate, as in the other substrates studied; absolutely no effect of [H$^+$] was observed. The [H$^+$] effect as noticed in this study has been already reported in studies on the oxidation of organic compounds such as aldehydes[14,15] and ketones by peroxomonosulphate.

Table: 4 Effect of hydrogen ion

[H$^+$]x 10^{-2} mol /dm^3	0.5	2.0	3.0	5.0	10.0
k' x 10^{-5}, s^{-1}	21.69	23.04	--	24.39	26.10

[Substrate] = 3 x 10^{-2} mol dm^{-3},[PMS] = 2 x 10^{-3} mol dm^{-3},[μ] = 0.3 mol dm^{-3},Solvent= 40% aqueous acetonitrile (v/v) , T = 333 K

3. Effect of ionic strength on the rate of reaction

Ionic strength of the medium was varied by adding sodium bisulphate (mol dm^{-3}). It was seen that the variation of ionic strength has; only a marginal increase of rate with increase in μ was noticed (Table-5). This shows that the reaction takes place between a neutral molecule and a negative species.

Table: 5 Effect of ionic strength

μ x 10^{-1} mol /dm^3	1.0	2.0	3.0	4.0	5.0
k' x 10^{-5}, s^{-1}	-	22.7	23.04	24.71	26.79

[Substrate] = 3 x 10^{-2} mol dm^{-3},[PMS] = 2 x 10^{-3} mol dm^{-3},[H$^+$] = 0.02 mol dm^{-3}Solvent= 40% aqueous acetonitrile (v/v) T=333K

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4. Effect of temperature on the rate of the reaction

The reaction was studied at different temperature in the range 288-303K and the values of k' were determined from the pseudo first order plot Table-6. The energy of activation E_a was evaluated (Fig-3). The other activation parameters were calculated and are presented (Fig-4,Table-7).

Table: 6 Effect of temperature

[Isatin] $\times 10^{-2}$ mol dm^{-3}	k'$\times 10^{-4}$ s^{-1}			
	288 K	293 K	298 K	303 K
2.0	2.3413	3.4928	5.7114	8.4827
2.5	2.9171	4.5369	6.9435	10.7473
3.0	3.5696	5.4619	8.2370	12.5513
3.5	4.2605	6.3217	9.8760	14.2780
4.0	4.6827	7.2813	11.0313	17.1957

Table-7: Rate and activation parameters

Energy of activation [Ea] KJ mol^{-1}	36.36
Enthalpy of activation [$\Delta H^{\#}$] KJ mol^{-1}	33.59
Entropy of activation [$\Delta S^{\#}$] J K^{-1}mol^{-1}	-185.46
Free energy of activation [$\Delta G^{\#}$] KJ mol^{-1}	95.35
log A	6.59

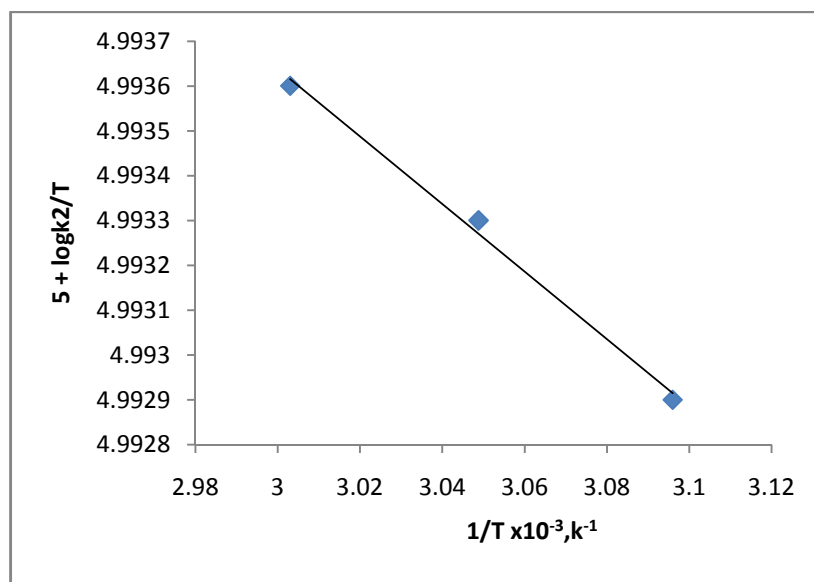**Fig.3 Eyring's plot for the oxidation of isatin by peroxomonosulphate**

Fig-4 Evaluation of Ea for the oxidation of isatin by peroxomonosulphate

5.Rate Equation

Based on the foregoing kinetic observations made such as dependence of rate on concentration, [H$^+$], μ and solvent effect, the following rate equation was suggested:

$$Rate = -\frac{d[PMS]}{dt} = k' = k_2[H^+] + k$$

Corresponds to rate equation for isatin which shows first order dependence of rate on [H$^+$] and the plot of k'(s^{-1}) Vs [H$^+$] is linear with an intercept on the ordinate.The rate enhancing effect of [H$^+$] observed in these systems points to (i) the protonated form of isatin being more reactive than their neutral forms and (ii) increased electrophilic activity of the oxidant species.

6. Test for free radicals on the rate of the reaction

As the peroxo anion is the oxidant in peroxomonosulphate, peroxodisulphate, etc., were able to undergo free radical reactions involving the production of SO$_4^{\bullet-}$, OH$^{\bullet}$, etc., it was thought to check whether any such free radicals were formed in the present reactions studied. The check for any such free radicals was carried out by looking for polymer formation by using a deaerated reaction mixture containing the reactants and a suitable freshly distilled or

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recrystallised monomer like acrylamide and acrylonitrile. There was no induced polymerisation confirms that the reaction follows ionic pathway.

7.Effect of dielectric constant

The solvent plays an important role by altering the rate. Acetonitrile is both a weaker base and weaker acid than water. Therefore in acetonitrile isatin will exist as neutral species. . This was further confirmed by the addition of allylacetate, an effective radical inhibitor, which did not alter the reaction rate. The reactions were carried out in aqueous acetonitrile medium with a dielectric constant (37.5) different from that of pure water (80). The effect of dielectric constant on the reaction rate by varying the percentage of acetonitrile in the reaction mixture (30-55% v/v) was studied. The rate of the reaction was found to decrease with increase in the percentage of acetonitrile (i.e,) with decrease in dielectric constant of the reaction mixture. This indicates that there is a charge development in the transition state involving a more polar activated complex than the reactants [16], a neutral molecule [isatin] and a negative ion (HSO_5^-) and absence of ion-ion or dipole-dipole type mechanism, which was also supported by the highly negative $\Delta S^{\#}$ values obtained in this work [17]. (Table 8)It may also be noted that the more negative $\Delta S^{\#}$ values of this work as reported earlier in many peroxomonosulphate-organic systems [18] point to a polar mechanism.

Table: 8 Effect of dielectric constant

% of acetonitrile	30	40	45	50	55
k' x 10^{-5}, s^{-1}	48.74	23.04	18.49	12.70	---

[Substrate] = 3 x 10^{-2} mol dm^{-3},[PMS] = 2 x 10^{-3} mol dm^{-3},[H^+] = 0.02 mol dm^{-3}[μ] = 0.3 mol dm^-3,T=333K

8.Mechanism

Based on the above results the following ionic mechanism was proposed. The reaction proceeds through and electrophilic attack of the oxidant (peroxomonosulphate) at the neucleophilic site C3 of isatin. From the experimental observations it was suggested that in this system the first step is the protonation of isatin to carbonium ion intermediate (2). The nucleophilic attack of peroxo anion takes place at C3 leading to the formation of intermediate (3). The intermediate 3 undergoes lactonisation to yield the products 4[19, 20]. Formation of this product was already reported [21] for similar type of oxidant [20-24].The identify of this product isatoic anhydride (4) was confirmed from its ^{1}H NMR and FT-IR spectra. FT-IR (KBr) 3421, 1760 - 80 cm^{-1} , ^{1}H NMR (DMSO) ppm = 6.8 - 8.1 (m, 4-ArH, NH).

Isatin (1), (2), (3), Isatoic anhydride (4)

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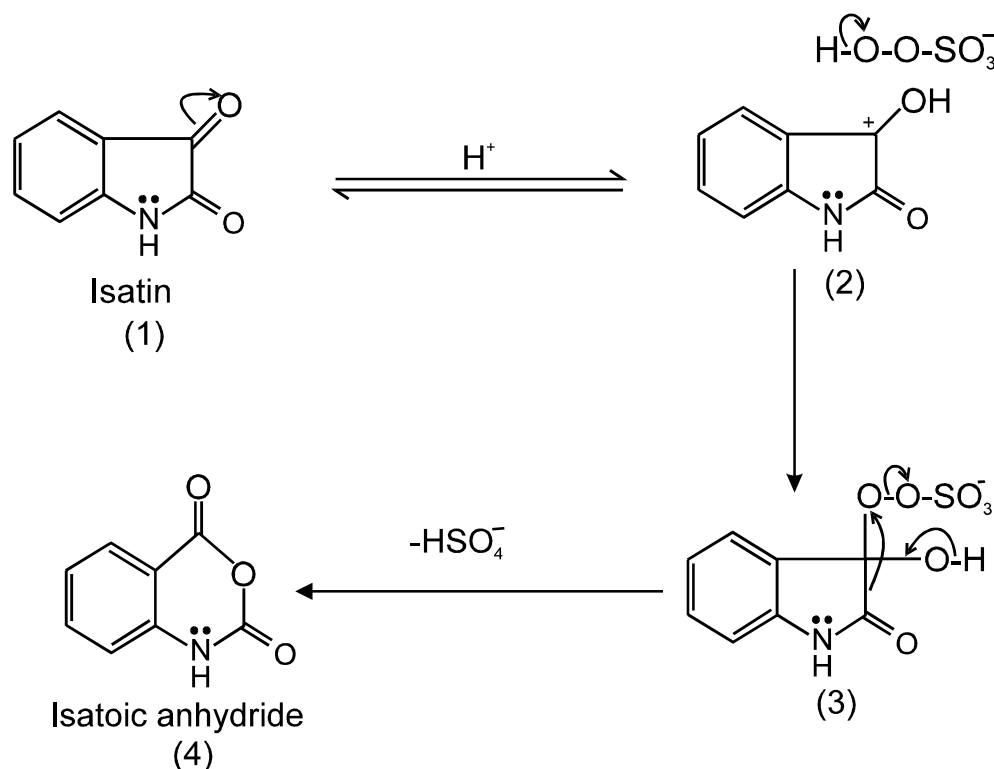
CONCLUSION

The reaction between isatin and peroxomonosulphate follows ionic mechanism in acetonitrile medium. The main active species of peroxomonosulphate is considered as peroxoanion. The nucleophilic attack of peroxo anion takes place leading to the formation of intermediate which subsequently decomposes to the product isatoic anhydride. The description of the mechanism was consistent with experimental evidences.

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